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DENITRIFICATION IN THE ELK VALLEY AQUIFER, NORTHEASTERN NORTH DAKOTA

by

Gale G. Mayer
Master of Science, University of North Dakota, 1988

A Dissertation

Submitted to the Graduate Faculty

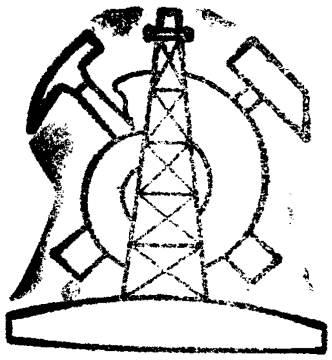
of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Doctorate of Philosophy



Grand Forks, North Dakota
December
1992

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This dissertation, submitted by Gale G. Mayer in partial fulfillment of the requirements for the Degree of Doctor of Philosophy from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Philip J. Gerla

David J. Klenka

Ronald Matheney

Gale W. Sellen

John R Reid

This dissertation meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Harvey Knull

Dean of the Graduate School

12-1-92

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PERMISSION

Title Denitrification in the Elk Valley aquifer, Northeastern North Dakota

Department Geology and Geological Engineering

Degree Doctorate of Philosophy

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Date 12/7/92

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Finally I am gratefully indebted to my wife, Wendy, who gave me emotional support and understanding throughout my graduate program.

ABSTRACT

Biological denitrification controls nitrate distribution in the Elk Valley aquifer, which underlies approximately 725 square kilometres of northeastern North Dakota and provides drinking water for farms and rural communities in the area. Increased irrigation has raised concerns over potential contamination from agricultural practices. The purpose of this study was to establish the role of biological denitrification in minimizing concentration and distribution of nitrate and to determine the effect irrigation practices have on groundwater flow and nitrate distribution in the saturated zone.

The aquifer is unconfined and consists of up to 20 metres of glacial outwash and deltaic shale-rich sand deposits. The water table ranges from two to five metres below the surface. Groundwater flows to the southeast at an average velocity ranging from 4.2×10^{-7} to 1.6×10^{-6} metres per second.

Nitrate (as NO_3-N) was detected only in wells completed at depths less than three metres below the water table and ranged from 5 to 21 mg/L at the 0 to 1.5 metre level and

from 2 to 6 mg/L at the 1.5 to 3 metre level. Dissolved oxygen was near saturation in the upper 1.5 metres of the saturated zone and less than 1 mg/L in the deeper wells. Dissolved organic carbon ranged from 18.7 to 91.4 mg/L. Biological oxygen demand, which can be used to indicate biodegradable organic carbon, was not detected in the upper 1.5 metres of the saturated zone and ranged from 4 to 6 mg/L at greater depths. Ammonia was not detected in the upper three metres of the saturated zone and was present at concentrations below 1 mg/L in the deeper wells. Denitrifying bacteria were found to be present throughout the aquifer.

Intermittent pumping of an irrigation well was found to affect groundwater flow and the vertical displacement of contaminants. Numerical modeling of particle movement indicated a sine-wave path with upward movement during periods of irrigation pumping and downward movement during periods of recovery in the upper part of the aquifer. In addition, overall upward movement of particles occurred at distances greater than 30 metres from the irrigation well in the upper part of the aquifer. Near the irrigation well, there was a strong downward movement of particles even during periods of recovery because of the vertical contrast in hydraulic heads that result from pumping.

INTRODUCTION

Purpose

The Elk Valley aquifer underlies 725 square kilometres of northeastern North Dakota and is an important source of water for farms and rural communities in the area. Drought conditions in North Dakota during 1988-1990 made irrigation desirable. Forty-eight irrigation systems were in the Elk Valley aquifer of western Grand Forks County in early 1991, with 53 applications pending (Tonneson, 1991). This increase in irrigation has raised concerns over the depletion of water and the potential for nitrate contamination of the aquifer. The purpose of this study was to determine the impact of irrigation on groundwater quality and establish the role of biological denitrification in minimizing concentration and distribution of agricultural nitrate in a surficial glacial aquifer.

Nitrate in groundwater is of concern because of its potential health effects. Ingestion of nitrate by infants may lead to "methemoglobinemia" or "blue-baby syndrome" (Comly, 1945). When ingested, nitrate is converted to

nitrite and passed into the blood stream (Shuvel and Gruner, 1972). There, nitrite bonds to ferric iron inhibiting oxygen transport by the blood (Jaffe, 1981). More recent evidence suggests that long-term ingestion of nitrate is involved with the etiology of human cancer (Fraser and Chilvers, 1980). Furthermore, the occurrence of elevated concentrations of nitrate in groundwater may indicate a greater likelihood of the presence of other contaminants such as pesticides.

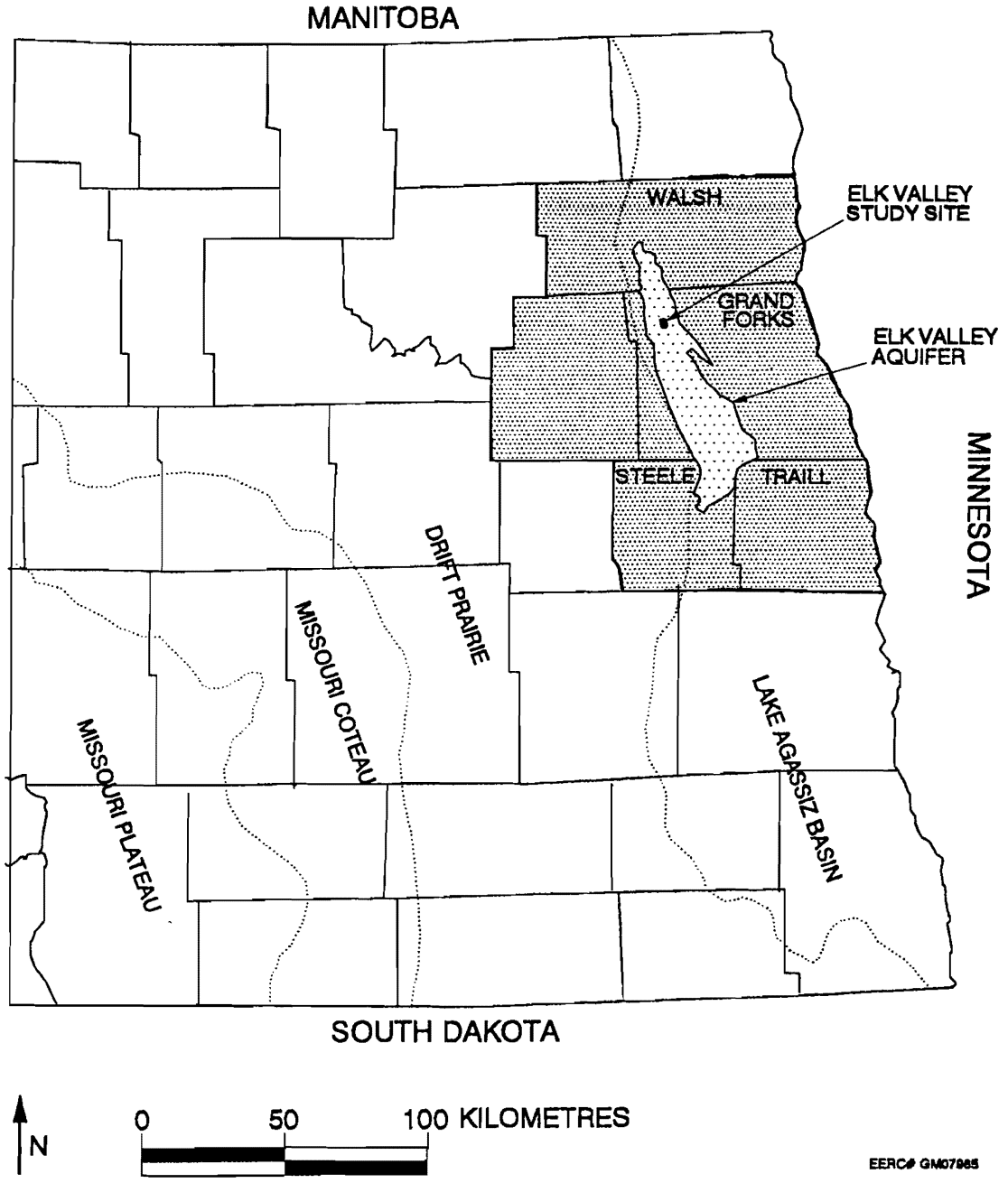
Denitrification in saturated soils has been an area of rapidly expanding interest and research (Korom, 1992). Denitrification is a biologically mediated reaction in which nitrate and nitrite are converted to gaseous forms of nitrogen (Korom, 1992). The role of denitrification in controlling nitrate contamination of surficial glacial aquifers in the northern Great Plains is not known. Objectives of this study were to determine the distribution of nitrate in groundwater at an irrigated site overlying the Elk Valley aquifer, to determine the role of biological denitrification in controlling nitrate distribution, and to determine whether there is a potential for irrigation to affect the denitrification process.

Site Selection and Location

The selection of a field site to investigate the role of denitrification on nitrate occurrence was based on several factors. Requirements included a shallow water table (3 to 5 metres), permeable soils in both the unsaturated and saturated zones, small vertical and horizontal gradients, and a recent initiation of irrigation. These selection criteria maximize the potential for obtaining a site where denitrification occurs, and allows the effect of irrigation on water quality to be determined. The long-term effects of irrigation on water quality are being monitored by changes in groundwater chemistry from the initiation of irrigation over a several year period in which irrigation is practiced.

A 65-ha site in Section 16, Agnes Township, northwestern Grand Forks County (Figure 1) met these requirements and was selected for study. The site overlies the Elk Valley aquifer, which is one of the more important sources of water in eastern North Dakota (Kelly and Paulson, 1970, p. 23-32). The water table ranges from 2 to 5 metres below ground surface. An irrigation system was installed at the site in the fall of 1989. Crops grown at the site include potatoes, which are grown in alternating years and rotated with corn, small grains, or beans.

Figure 1. The Elk Valley aquifer and study site.


MANITOBA
WALSH
ELK VALLEY STUDY SITE
GRAND FORKS
ELK VALLEY AQUIFER
STEELE
TRAILL
MINNESOTA
DRIFT PRAIRIE
MISSOURI COTEAU
MISSOURI PLATEAU
LAKE AGASSIZ BASIN
SOUTH DAKOTA
N
0
50
100 KILOMETRES
EERC# GM07985

Site Geology

The Elk Valley aquifer is on the western margin of the glacial Lake Agassiz basin of eastern North Dakota. Lake Agassiz, a large proglacial lake during the latter part of the Pleistocene epoch (10,000 to 15,000 years before present), is underlain by glacial drift, westward-dipping Paleozoic and Mesozoic sedimentary rocks, and Precambrian igneous and metamorphic rocks (Hansen and Kume, 1970, p. vii-viii). In the vicinity of the study area, the aquifer is bordered to the east by the Edinburg end moraine and to the west by the Pembina escarpment. The Pembina escarpment is the transition zone between the glacial Lake Agassiz basin and the westward-lying Drift Prairie.

The Edinburg end moraine, a narrow, discontinuous, sandy till ridge, extends from McCanna to Edinburg in Walsh County, a distance of approximately 56 kilometres. The segment of the end moraine in Grand Forks County is about 18 kilometres long, commonly less than two kilometres wide, and up to 23 metres high (Hansen and Kume, 1970, p. 42). The end moraine is partially buried by lake sediments and outwash in the vicinity of the study area and completely covered by these sediments south of McCanna.

The Elk Valley aquifer consists of up to 20 metres of unconfined outwash and deltaic sand and gravel. The aquifer underlies approximately 725 square kilometres of

northeastern North Dakota, including parts of Walsh, Grand Forks, Traill, and Steele Counties (Figure 1). There is a general gradation of texture from coarser sediments in the north to finer sediments in the south (Kelly and Paulson, 1970, p. 23-32).

Grand Forks County is characterized by a dry subhumid climate with a wide temperature range, variable precipitation, and rigorous winters (Hansen and Kume, 1970, p. 2-3). The growing season averages 132 days and annual precipitation is 7.55 centimetres, of which over three-fourths falls during May through September (Hansen and Kume, 1970, p. 2-3).

Because the Elk Valley sediments are characterized by permeable sands that readily absorb rainfall and snowmelt, large tracts of deposits are undissected by streams (Kelly and Paulson, 1970, p. 23-32). Groundwater flows to the east in most parts of the aquifer, although groundwater flow direction is locally affected by streams and other features such as the Edinburg end moraine. Discharge from the aquifer is mainly through springs in the valleys of the Forest and Turtle Rivers and by evapotranspiration (Kelly and Paulson, 1970, p. 23-32).

The soil at the 65-ha study area is a sandy loam of the Inkster Series. The Inkster sandy loam is characterized by a black sandy loam topsoil approximately 15 centimetres

thick and a sandy loam subsoil approximately 45 centimetres thick (Doolittle et al., 1981, p. 46).

Previous Work

The most common contaminant identified in groundwater is dissolved nitrogen in the form of nitrate and this contaminant is becoming increasingly widespread because of anthropogenic sources (Freeze and Cherry, 1979, p. 413). In a study of Grand Forks County groundwater quality, Kelly (1968, p. 116-117) reported nitrate concentrations (as NO_3-N) in excess of 10 mg/L in several samples from the Elk Valley aquifer. An increase in irrigation and associated fertilizer usage has raised concerns over the potential for contamination of the aquifer (Tonneson, 1991).

Biologically mediated nitrate loss can occur through at least three different pathways (Bartlett et al., 1979). One of these, not considered to be true denitrification, is an assimilatory pathway in which the uptake of nitrate results in bacterial cell protein. The other two pathways are dissimilatory and can be distinguished by the end products. One of these results in the formation of ammonia which is not necessarily utilized by the denitrifying bacteria (Bartlett et al., 1979). The other dissimilatory pathway,

which is considered to be true denitrification, results in the formation of nitrogen gas (N_2) or nitrous oxides.

Denitrification can be defined as a biologically mediated reduction reaction in which nitrate or nitrite is converted to gaseous forms of nitrogen (Tiedje, 1982). It is a respiratory reaction very similar to electron transport by oxygen, with the substitution of nitrate or nitrite for the oxygen. In respiration, oxygen is the terminal electron acceptor and is reduced to water. In denitrification, nitrate or nitrite are the terminal electron acceptors, and they are reduced to nitrogen gas (N_2) or gaseous nitrogen oxides.

Denitrifying microbes are mainly heterotrophic, meaning they use organic compounds for their source of carbon and energy. Hence, organic matter must be available for them to denitrify and grow. Additionally, these microbes are actually considered to be aerobic and will use oxygen exclusively, if it is available in sufficient quantities. If oxygen becomes limiting and nitrate or nitrite are available, these microbes will continue to respire using these alternate sources.

Abiotic nitrate reduction was discussed by Korom (1992), who questioned whether nitrate removal was independent of denitrifying bacteria. Lind and Pedersen (1976) reported that nitrate ions were never found when water contained ferrous ions. They attributed this absence of nitrate to

the abiotic reduction of nitrate in the presence of iron. They failed, however, to demonstrate the process was abiotic (Lind and Pedersen, 1976). Although additional research is required to determine the importance of abiotic nitrate reduction, it is generally accepted that denitrification is mainly a biologically mediated process.

Previous work has largely focused on the role of denitrification in the unsaturated zone or in soils. A summary of this work will be made before discussing the role of denitrification under saturated conditions.

Unsaturated zone denitrification

General

Soil bacteria were first observed to be capable of reducing nitrate to molecular nitrogen and nitrous oxides by Gayon and Dupetit (1886). Since then, this process has been studied extensively.

Factors which may influence denitrification in soils include 1) dissolved oxygen concentration, 2) organic matter, 3) pH, 4) moisture content, 5) temperature, and 6) nitrate concentration. Excellent reviews of the topic are provided by Broadbent and Clark (1965) and Knowles (1982). A short summary of the role of each of these factors follows.

Dissolved oxygen

Enzymatic denitrification is a biological process in which facultative anaerobic bacteria use nitrate in place of oxygen as a electron acceptor (Broadbent and Clark, 1965). Although there have been conflicting reports on the effect of oxygen on the denitrification reaction in the past, it is now generally accepted that dissimilatory nitrate reduction becomes dominant only under anaerobic conditions (Delwiche and Bryan, 1976). In soils where denitrification has been reported to occur under apparently aerobic conditions, it is believed that denitrification occurs at anaerobic sites in the soil matrix (Burford and Bremner, 1975).

In the unsaturated zone, the soil matrix frequently consists of water-filled pores in contact with air. The dissolved oxygen concentration in the water-filled pores depends on the oxygen consumption rate, the oxygen diffusion rate, the geometry of the diffusion path, and probably other factors which may allow anaerobic conditions to exist and denitrification to occur (Knowles, 1982).

Organic matter

The effect of organic matter on denitrification is important and in many cases may be the limiting factor in the denitrification process. Because reduction of nitrate to nitrogen gases is endoergic, an oxidizable substrate must provide energy for the growth of bacteria and serve as an

electron donor for the denitrification process (Broadbent and Clark, 1965). Also, the presence of organic matter and the rate of its decomposition has a direct influence on oxygen demand and as a result may influence the oxygen concentration and whether denitrification can occur.

Denitrification capacities of soils were significantly correlated with total organic carbon and very highly correlated with water-soluble organic carbon (Burford and Bremner, 1975). Burford and Bremner (1975) concluded that denitrification in soils under anaerobic conditions is controlled largely by the supply of readily decomposable organic matter.

pH

Denitrification rate was related to pH by Knowles (1982). He found the optimum rate for denitrification to range between pH 7.0 and 8.0. The proportion of various nitrogen gases were found to be pH dependent by Wijler and Delwiche (1954). Below pH 7, N_2O was the major product of denitrification. Above pH 7, N_2O was still produced in excess of N_2 but it was subsequently reduced to N_2. They also found that NO was produced in equal volumes to N_2O at low pH (~4.9). The pH may also affect the availability of soil organic matter to microorganisms (Nommik, 1956).

Moisture content

Denitrification was not found in soils in which the water content was less than 60-70 percent of the water holding capacity of the soil (Nommik, 1956). Increasing water contents corresponded with more favorable denitrification conditions. Nommik (1956) surmised that higher water contents inhibit the diffusion of oxygen into the soil making conditions for denitrification more favorable.

Temperature

Nommik (1956) found the optimum temperature for denitrification to be between 60 and 70°C with denitrification being negligible at 3°C but considerable at temperatures of 12-13°C. He also reported that nitrous oxide dominates at lower temperature but molecular nitrogen is the main product at higher temperatures.

Nitrate concentration

Nitrate concentrations in soil were found not to influence the rate of denitrification (Wijler and Delwiche, 1954). Nommik (1956), however, reported that reduction of nitrous oxide to molecular nitrogen does not occur until most nitrate is consumed.

Saturated zone denitrification

General

Conditions required for saturated-zone denitrification include the presence of denitrifying bacteria, the existence of reducing conditions, and the availability of an adequate supply of labile (readily biodegradable) organic carbon (Starr and Gillham, 1989). Because the end products of denitrification are nitrogen and nitrous oxides, which are typically present in groundwater, direct measurements of these gases in the saturated zone does not necessarily provide evidence for denitrification. As a result, most work has focused on determining whether conditions are favorable for denitrification, whether nitrate is present, and where nitrate occurs in the aquifer.

Organic matter

The amount of labile organic carbon present probably controls denitrification in the groundwater zone. Starr and Gillham (1989) found that under shallow water-table conditions, organic carbon was sufficient to reduce dissolved oxygen and provide conditions favorable for denitrification. Under deeper water table conditions, there was insufficient organic carbon to provide a substrate for dissolved oxygen and nitrate reduction.

Their study indicates that the soil zone provides a source of organic matter and that the amount of organic

carbon reaching the water table depends on the depth to the water table. They further suggested that the occurrence of denitrification in groundwater is related to the residence time of infiltrating water in the vadose zone and transformations to organic matter during transport in this zone.

Redox potential

Variations in redox potential (Eh) and the concentration of inorganic species can be related to a sequence of oxidation-reduction reactions and related microbial catalysis (Champ et al., 1979). In fact, microorganisms are believed to catalyze nearly all the important redox reactions in groundwater (Freeze and Cherry, 1979, p. 121-123).

Three redox zones are commonly associated with groundwater flow systems (Champ et al., 1979). The first and commonly the shallowest of these zones is characterized by the presence of oxygen and nitrate. The second redox zone is characterized by the lack of oxygen and nitrate, which have been reduced to carbon dioxide, nitrogen, and nitrous oxides. The reduced forms of iron and manganese, more soluble in water than oxidized forms, are present in higher concentrations. In the third redox zone, sulfate is reduced to sulfide. Sulfide may be present as hydrogen sulfide or a precipitate such as iron sulfide. Gillham and

Cherry (1978) found that aerobic conditions and nitrate contamination are generally limited to depths of one to two metres below the water table in aquifers whose water table is less than two to three metres below the ground surface.

Denitrifying bacteria

Microorganisms can be divided into two broad classes with respect to their energy and carbon sources (Alexander, 1977, p. 32-34). Heterotrophic microorganisms require organic carbon as a source for energy and carbon. Autotrophic microorganisms obtain their energy from sunlight or by the oxidation of inorganic compounds and their carbon through the assimilation of CO_2. Most denitrifying bacteria of significance in soil are heterotrophic and aerobic (Tiedje, 1982). The genus Pseudomonas includes the most common heterotrophic denitrifying bacteria isolated from soils (Gamble et al., 1977).

Substantial microbiological populations are known to exist in groundwater (Lowrance and Pionke, 1989). Little is known of the ecology of the communities and few studies have identified the types of denitrifying bacteria present in groundwater systems. Foster et al. (1985) were able to isolate Pseudomonas sp. bacteria in a denitrification study of the Chalk aquifer in eastern England. Bacteria which form biofilms on the surfaces of solid particles predominate in the saturated zone (McCarty et al., 1984), although

Matthes (1985) found that in sand aquifers, most bacteria occur in the groundwater.

Studies on autotrophs include denitrification in the presence of reduced sulfur and iron. The current knowledge on autotrophic denitrification was summarized by Korom (1992) who includes a discussion of inorganic nitrate reduction in the presence of iron (Fe^{+2}). Lind and Pedersen (1976) reported that nitrate ions were never found when water contained ferrous ions. They attributed this absence of nitrate to abiotic nitrate reduction in the presence of reduced iron. Attempts to demonstrate the denitrification was abiotic, however, failed (Lind and Pedersen, 1976). Korom (1992) indicated that Gallionella ferruginea, an autotrophic bacterium that can denitrify in a reduced-iron environment, if present, could partially explain why groundwater low in organic carbon and in a reduced-iron environment has an absence of nitrate.

Methods to establish the occurrence of denitrification

The only methods known for determining denitrification are based on the consumption of nitrate or nitrite or on the detection of resultant gaseous products (Tiedje, 1982).

Measurement of nitrate loss provides the simplest indirect method for determining denitrification. This procedure is acceptable if measurable amounts of nitrate are not assimilated by the microorganisms or reduced to ammonia

through dissimilatory reduction. Most studies have used this indirect method to establish whether biological denitrification does or can reduce nitrate in groundwater (Lowrance and Pionke, 1989).

The use of nitrate/chloride or nitrate/bromide ratios is an indirect measurement based on the assumption that bromide or chloride concentrations are conservative during transport through the soil column. Trudell et al. (1986) injected nitrate and bromide into a shallow sand aquifer in Ontario, Canada and integrated changes in the nitrate to bromide ratio as an indication of denitrification in the saturated zone. In addition, they observed increases in bicarbonate and populations of denitrifiers which would also be expected if denitrification was responsible for the nitrate reduction.

The most commonly used method for direct measurement of denitrification is the acetylene inhibition method. During denitrification, nitrate is reduced to N_2O and then N_2. The method is based on the observation that acetylene at a concentration of about 0.01 atm inhibits the reduction of N_2O to N_2 (Hauck, 1986). A closed chamber isolates a volume of soil under a blanket of acetylene, inhibiting N_2O conversion. The N_2O is measured, providing evidence of denitrification. Although this method is well suited for laboratory testing of denitrification where closed chambers can be used, it is difficult to completely inhibit N_2O

reduction in a field setting. Limitations of the acetylene blockage technique for field measurement of denitrification are discussed by Rolston (1986).

The most reliable technique for the direct establishment of denitrification in the laboratory is the use of ^{15}N-labeled nitrate. Labeled nitrate can be used as a tracer provided that the nitrogen-isotope concentration is measurably different from that of unlabeled nitrate in the system. The method is based on the loss of labeled nitrate and its conversion to labeled reduced-nitrogen products. Mass spectrometer analysis for isotopic composition indicates whether denitrification has occurred. This method is not readily adapted to field use either, because considerable sampling errors can result from spatial variability of nitrate movement (Hauck, 1986).

METHODS

The potential for denitrification to affect groundwater nitrate at the Elk Valley site was determined indirectly by measuring the distribution of nitrate. The presence of denitrifying bacteria and the concentrations of organic matter and dissolved oxygen were used to indicate whether conditions were suitable for biological denitrification to occur. Because bacteria are able to utilize only a portion of the dissolved organic matter present in groundwater, biological oxygen demand (BOD) tests were used as a measure of biodegradable organic carbon. BOD is an empirical test used to determine the relative oxygen requirements for the biochemical degradation of organic material.

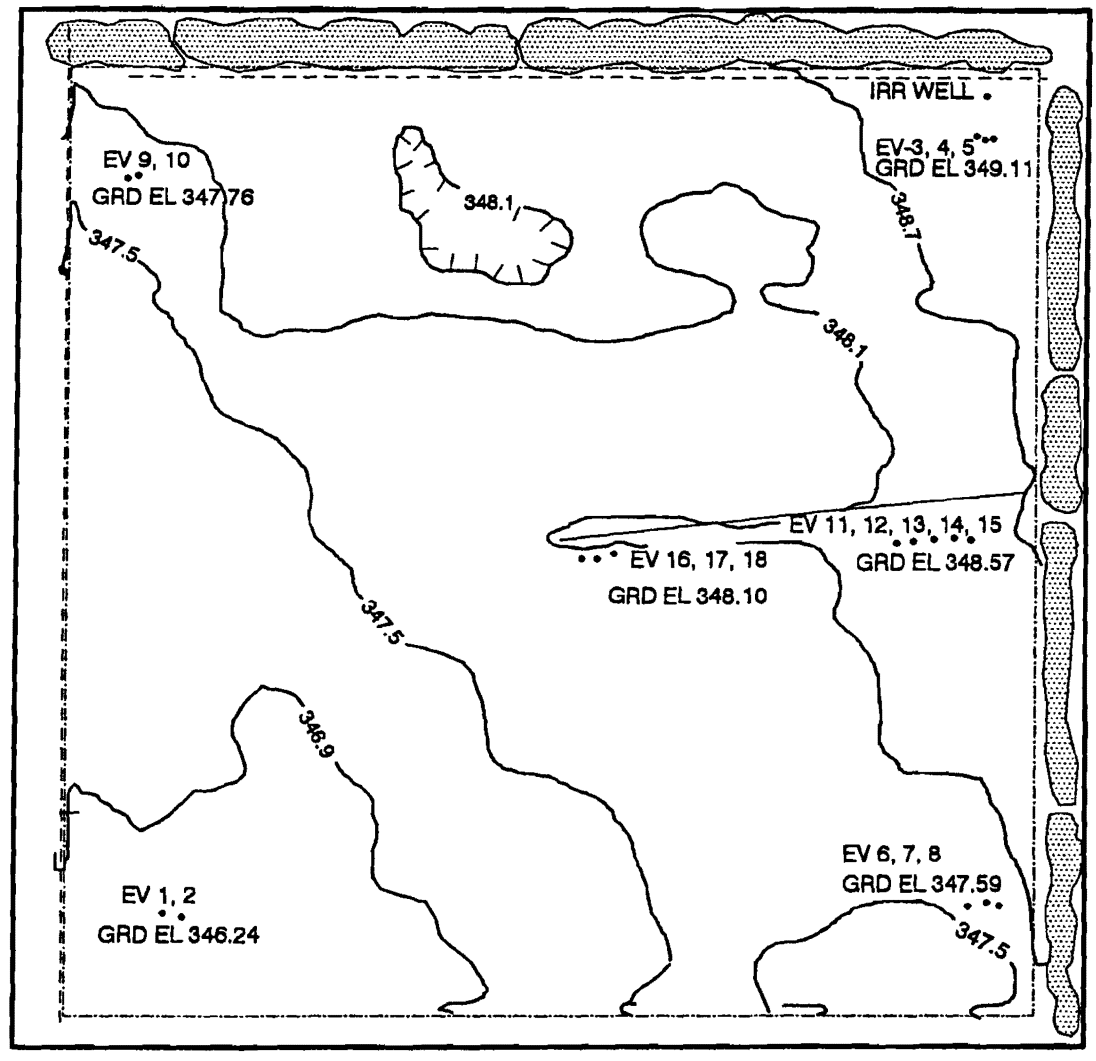
Groundwater monitoring wells were installed to characterize the hydrogeology of the site, including the hydraulic gradient, hydraulic conductivity, flow direction, and groundwater chemistry. The resulting data were used to determine the role of denitrification on nitrate distribution and the effect of irrigation on the potential for denitrification.

Site Instrumentation

Instrumentation at the 65-ha Elk Valley test site included monitoring wells, lysimeters (soil-water samplers), tensiometers, and neutron moisture-probe access tubes. Eighteen monitoring wells were placed in six separate locations. At each location there was one water table well and one well completed at the bottom of the aquifer. In addition, at several locations monitoring wells were screened at intermediate depths within the aquifer so that a vertical nitrate profile could be determined. Monitoring-well casings and screens were constructed using 316-stainless steel to allow for pesticide sampling. The 18 monitoring wells were installed with a hollow-stem-auger. The locations of the monitoring wells are indicated on a topographic map of the study site (Figure 2). Well completion data, including elevations of screened intervals, are given in Appendix II.

Lysimeters were constructed with 316-stainless steel bodies and teflon porous cups. Two groups of lysimeters were installed at the study site, one set in the vicinity of well EV-10 and one set near EV-13. Each group consisted of three lysimeters which were placed at 0.75, 1.5, and 2.5 metres below ground surface. A neutron access tube

Figure 2. Topography and monitoring well locations at the Elk Valley site.



EERC No. GM07987-041-S

consisting of 5 centimetre inner diameter (I.D.) by 3 metre long aluminum conduit pipe was placed near well EV-13. Neutron probe readings were obtained with a Campbell Pacific Nuclear Model 503 hydroprobe. One group of four tensiometers was placed near well EV-13. The septum-type tensiometers were obtained from Soil Measurement Systems and placed at 0.6, 1.2, 1.8, and 2.4 metres below ground surface. Measurements were made with a pressure transducer and meter.

Sampling

Samples from the monitoring wells were collected with 316-stainless steel bailers. Decontamination procedures included distilled-deionized water, methanol, acetone, and then distilled-deionized water rinses of all sampling equipment. A minimum of three casing volumes of water were removed from the monitoring wells before final sample collection. Samples were collected after each casing volume removal and checked for conductivity, pH, and temperature. To insure that final samples were representative of *in situ* groundwater, conductivity and pH measurements on consecutive samples were required to agree within 10 percent. Samples collected were passed through 0.45 micron disposable filters

and then preserved and stored for analysis according to standard EPA procedures (Appendix X).

Samples for biological and tritium analysis were also collected with a stainless steel bailer by procedures similar to those used for chemical analysis. Decontamination procedures did not include an acetone rinse, however, and samples were not filtered. Biological samples were collected in sterile bags suitable for storage.

Analyses

Samples were analyzed for dissolved oxygen, dissolved organic carbon, redox potential, nitrate, nitrite, ammonia, pH, conductivity, temperature, and selected inorganic constituents. A separate set of samples was collected for microbiological analysis. Results of all analyses are reported in SI units with the exception of temperature, which is reported as degrees Celsius.

Dissolved-oxygen, temperature, conductivity, pH, and redox were measured in the field. Dissolved-oxygen and temperature were measured within the wells using a YSI 5739 dissolved-oxygen probe with a YSI model 58 dissolved-oxygen meter. Redox potential was determined on water pumped from the monitoring well into a flow-through cell to avoid exposure of the water to oxygen. Measurements were made

with a Beckman 39273 platinum electrode and a Beckman PHI 12 Ph/ISE meter. Conductivity and pH measurements were made in the field to insure the integrity of samples collected for laboratory analysis. Field conductivity measurements were made with a Beckman Model RC-160 conductivity meter and field pH measurements were made with a Beckman PHI 11 Ph meter.

Laboratory analyses were conducted according to standard EPA and APHA procedures (Appendix X). Because of the frequency of nitrate analysis, a Hach DR-100 colorimeter (cadmium reduction method) was used. Standard nitrate solutions were prepared in the laboratory (4.51, 9.03, 15.80, and 20.32 mg/L as NO_3-N, respectively) and used to determine accuracy of the analyses ($\pm$1.3, $\pm$3.2, $\pm$6.8, $\pm$6.4 percent, respectively). In addition, comparison of the colorimetric method with ion chromatography indicated an error of $\pm$7 percent. The colorimeter was calibrated according to the manufacturer's specifications and included adjustment of the meter for sample color before adding reagent.

Microbiological analysis included colony forming units (CFU) for bacteria (APHA, 1980, p. 789-793) and most probable number (MPN) for denitrifiers (Tiedje, 1982). The media of Hutchinson et al. (1967) were used to determine if autotrophic denitrifiers were present.

Samples collected to determine tritium concentrations were sent to the Environmental Isotope Laboratory at the University of Waterloo for analysis. Samples were enriched by electrolysis (Taylor, 1977) and liquid scintillation counting (Drimmie et al., 1991) was used for the detection and quantification of tritium.

Hydraulic conductivity in the saturated zone was estimated from slug tests on selected monitoring wells using the method of Bouwer (1989). This method estimates the hydraulic conductivity of the aquifer around the screen of the well for fully or partially penetrating wells in unconfined aquifers. Wells were pressurized with nitrogen gas to depress water levels. The pressure was released through the use of a ball valve and the rate of recovery was measured with a pressure transducer and Thor data logger.

Hydraulic conductivity was also estimated using particulate distribution data obtained from sieve and hydrometer analysis of split-spoon samples collected during well installation. An empirical relation, $K = Ad^2$, was used where K is the hydraulic conductivity and d is the grain size diameter at which 10 weight percent of the soil particles are finer and 90 percent are coarser. For K (cm/sec) and d (mm), the coefficient A is equal to 1.0 (Freeze and Cherry, 1979, p. 350-352).

Modeling

A FORTRAN computer code for finite difference numerical modeling of groundwater flow, MODFLOW (McDonald and Harbaugh, 1988), was used to determine the horizontal and vertical hydraulic head distributions within the aquifer resulting from intermittent pumping of an irrigation well. The design of the model, including aquifer parameters and stress periods, are presented in Appendix XIII. The model was designed to simulate conditions at the Elk Valley study site and the operation of the irrigation system.

PATH3D 3.0 (Zheng, 1991), a groundwater path and travel-time simulator, was used to simulate particle movement in response to the changes in hydraulic head resulting from intermittent irrigation pumping. Input to PATH3D consisted of the hydraulic head output from MODFLOW, the initial location of the particles for tracking, and the period of particle tracking.

EXPERIMENTAL RESULTS

Hydrogeology

Based on visual and microscopic analysis of cores collected during drilling, there is a trend from quartz- and dolomitic-rich sands at the top of the aquifer to shale-rich sands towards the middle and bottom of the aquifer (Appendix I).

The groundwater hydrology was determined through the use of over 800 water level readings of 18 piezometers and water-table wells in the immediate study area. Water level data were collected over an 18 month period starting July 26, 1990 and ending January 30, 1992 (Appendix II and III).

Hydrographs for two of the water table wells are provided as Figures 3 and 4 (Wells EV-1 and EV-3, respectively). The general trend is for water levels to increase during the months of May, June, and July, with maximum water levels observed in July. Water levels tend to level off and then decrease at a slow rate for the remaining period.

Figure 3. Hydrograph for water-table well EV-1.

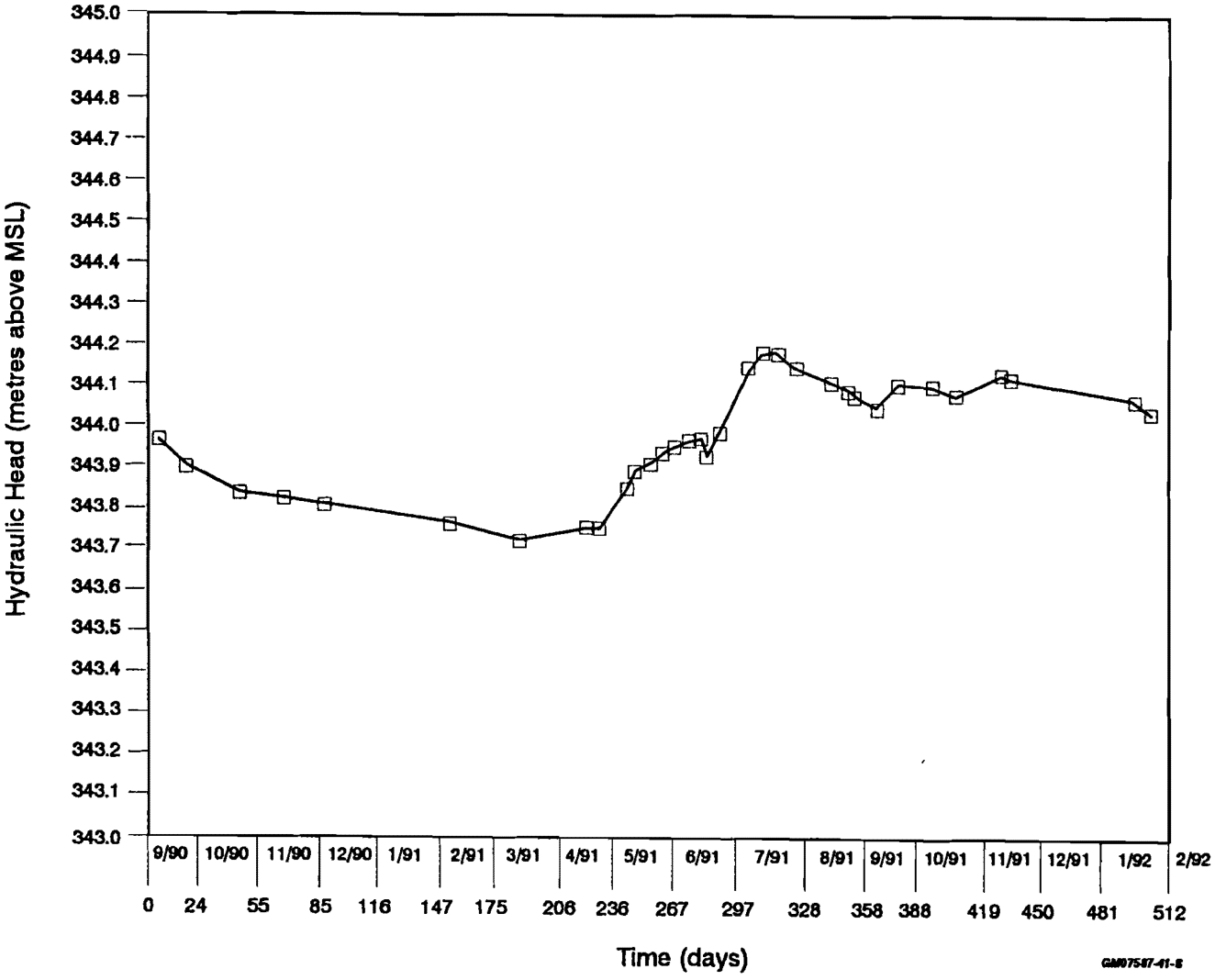
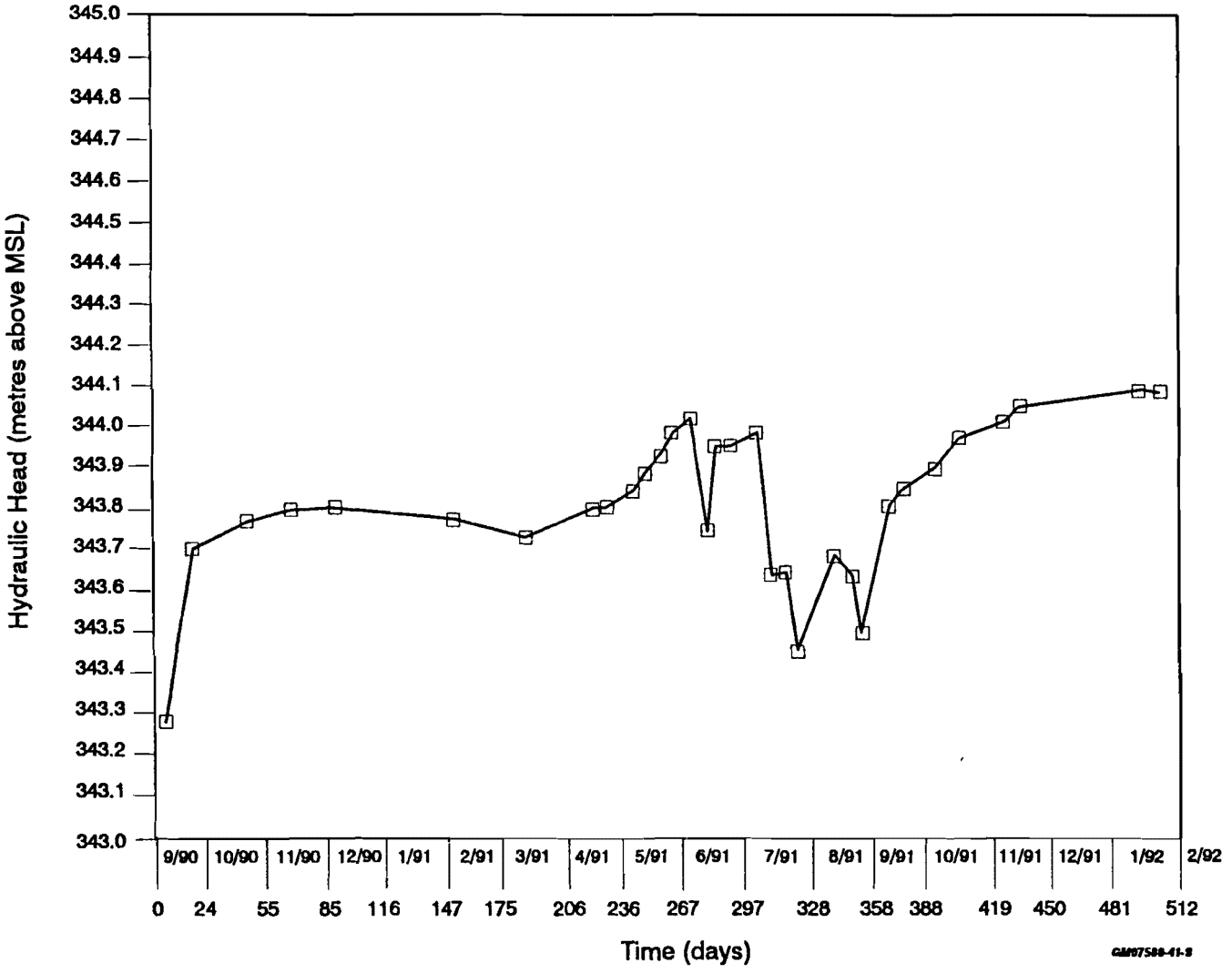

Hydraulic Head (metres above MSL)
345.0
344.9
344.8
344.7
344.6
344.5
344.4
344.3
344.2
344.1
344.0
343.9
343.8
343.7
343.6
343.5
343.4
343.3
343.2
343.1
343.0
9/90
10/90
11/90
12/90
1/91
2/91
3/91
4/91
5/91
6/91
7/91
8/91
9/91
10/91
11/91
12/91
1/92
2/92
0
24
55
85
116
147
175
206
236
267
297
328
358
388
419
450
481
512
Time (days)
GM07587-41-5

Figure 4. Hydrograph for water-table well EV-3.


Hydraulic Head (metres above MSL)
345.0
344.9
344.8
344.7
344.6
344.5
344.4
344.3
344.2
344.1
344.0
343.9
343.8
343.7
343.6
343.5
343.4
343.3
343.2
343.1
343.0
9/90
10/90
11/90
12/90
1/91
2/91
3/91
4/91
5/91
6/91
7/91
8/91
9/91
10/91
11/91
12/91
1/92
2/92
0
24
55
85
116
147
175
206
236
267
297
328
358
388
419
450
481
512
Time (days)
GM07588-41-8

The hydrograph of well EV-1 (Figure 3) shows a maximum change in water level of 0.46 metres for the reporting period. This water table well is approximately 950 metres southwest of the irrigation well and water levels do not appear to be influenced by pumping of the irrigation well. The minimum water level for this well was recorded in March of 1991, 343.72 metres above sea level. This reading occurred before spring recharge and after several years of drought conditions (1989 and 1990). The maximum water level recorded was 344.18 metres in July, 1991.

Figure 4 shows the change in water levels for EV-3, which is a water table well approximately 80 metres from the irrigation well. Although the general trend for water levels is the same as the other water table wells, several sharp decreases in water levels are evident during the summer months. These fluctuations in water level are the result of intermittent pumping of the irrigation well.

Potentiometric surface maps of the study site for 5 February 1991, 16 April 1991, and 30 January 1992 (Figures 5, 6, and 7 respectively) indicate that groundwater flow is to the southeast. The potentiometric surface map for 8 June 1991 (Figure 8), shows groundwater flow during the period most likely affected by spring recharge. Although general groundwater flow is toward the east-southeast in August 1991 (Figure 9), water levels are depressed in the vicinity of the irrigation well. Water levels at EV-3, which is the

Figure 5. Potentiometric surface map for February 5, 1991.

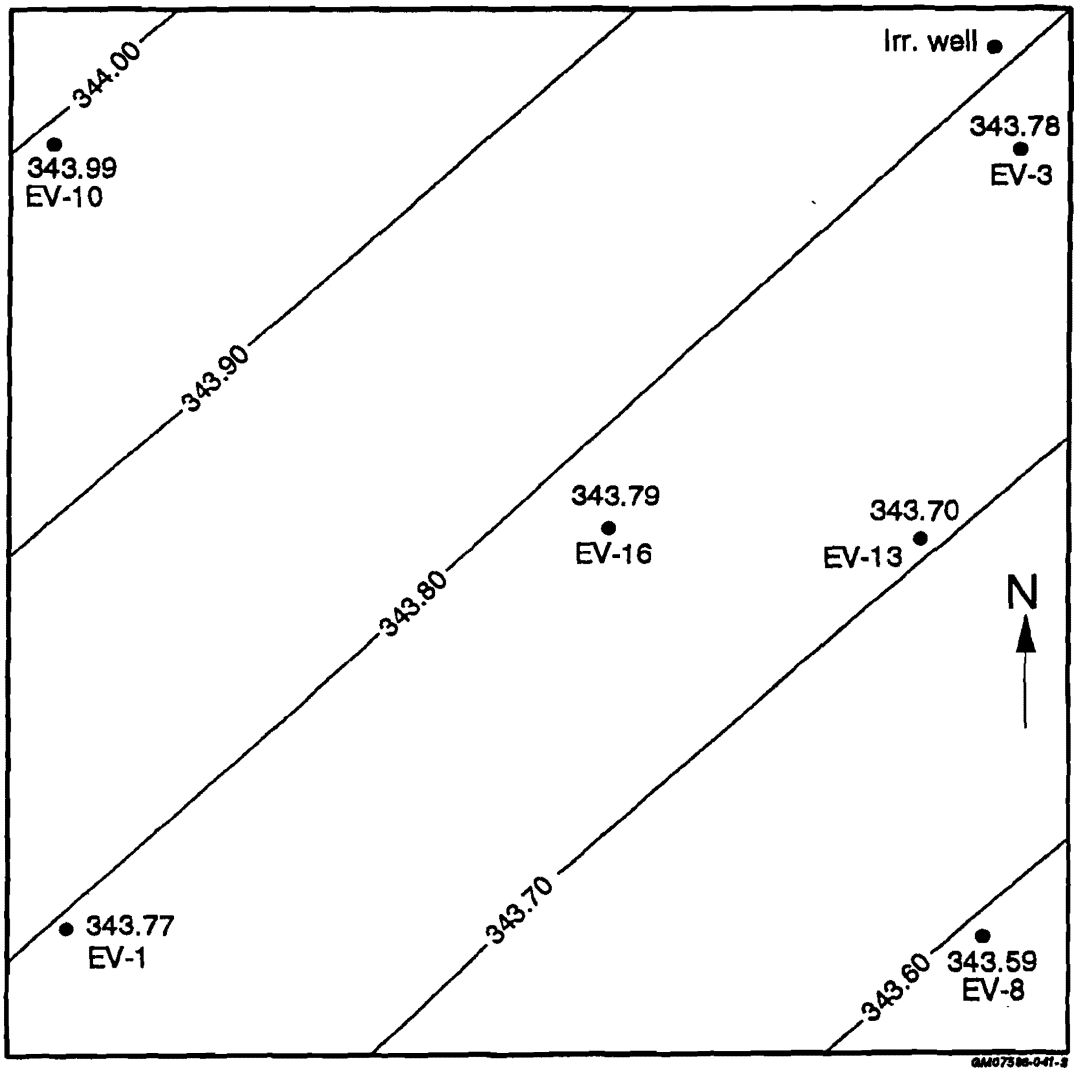

344.00
343.90
343.80
343.70
343.60
Irr. well
343.78
EV-3
343.99
EV-10
343.79
EV-16
343.70
EV-13
N
343.77
EV-1
343.59
EV-8

Figure 6. Potentiometric surface map for April 16, 1991.

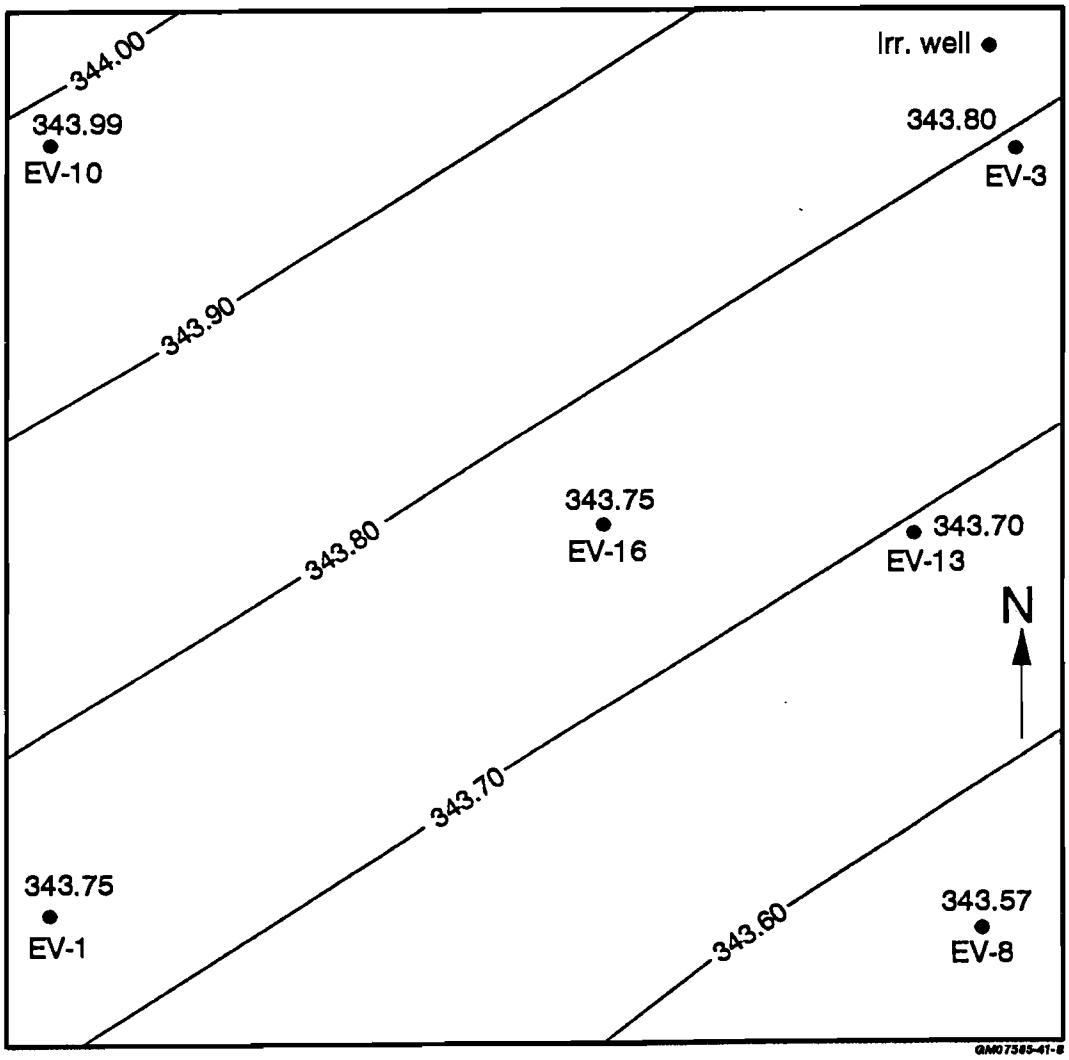

344.00
343.90
343.80
343.70
343.60
Irr. well
343.99
EV-10
343.80
EV-3
343.75
EV-16
343.70
EV-13
N
343.75
EV-1
343.57
EV-8
GM07585-41-8

Figure 7. Potentiometric surface map for January 30, 1992.

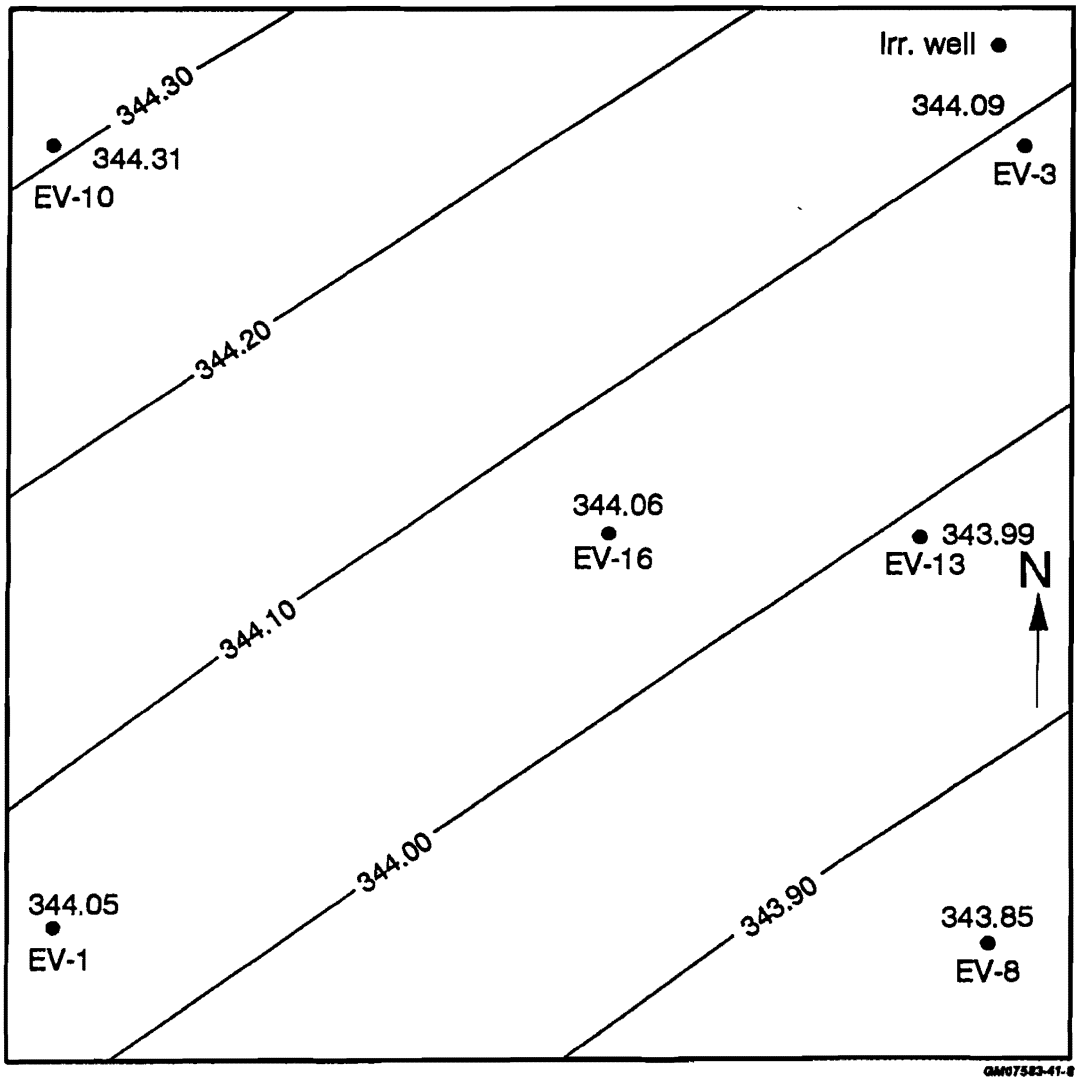

Irr. well
344.09
EV-3
344.30
344.31
EV-10
344.20
344.06
EV-16
343.99
EV-13
N
344.10
344.00
344.05
EV-1
343.90
343.85
EV-8
GM07583-41-8

Figure 8. Potentiometric surface map for June 8, 1991.

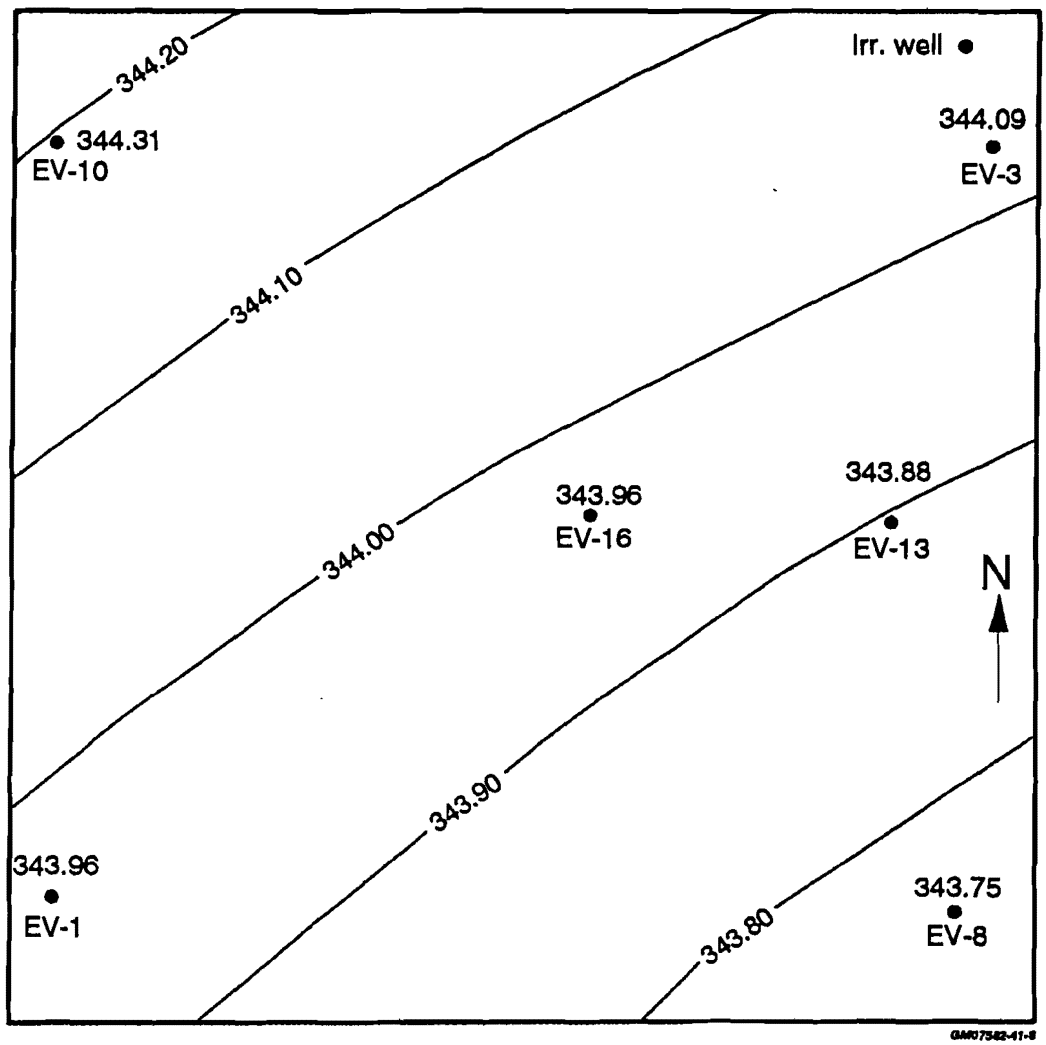
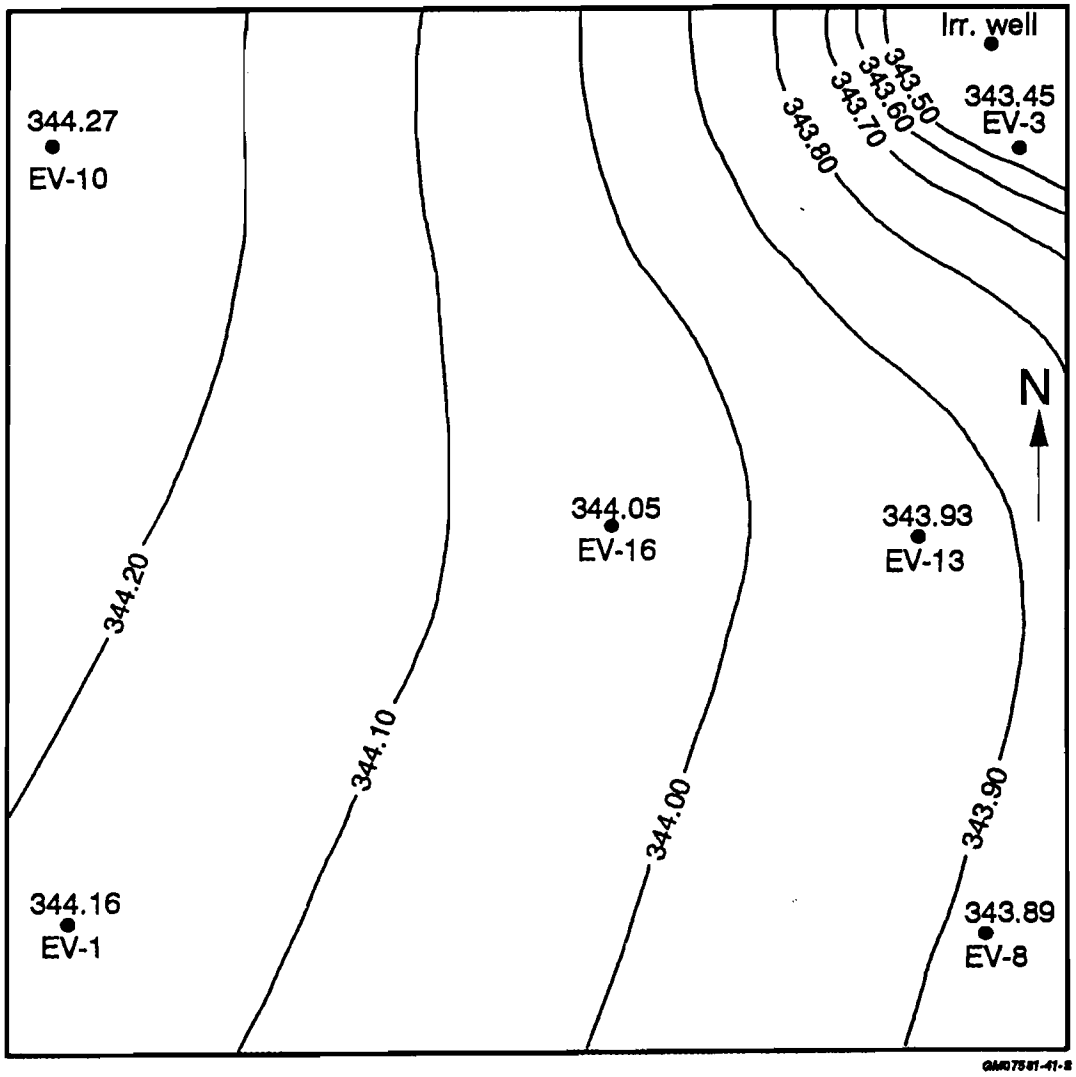

344.20
Irr. well
344.09
344.31
EV-10
EV-3
344.10
343.88
343.96
EV-16
344.00
EV-13
N
343.90
343.96
EV-1
343.75
343.80
EV-8

Figure 9. Potentiometric surface map for August 1, 1991.


Irr. well
343.45
EV-3
343.50
343.60
343.70
343.80
344.27
EV-10
N
344.20
344.10
344.05
EV-16
344.00
343.93
EV-13
343.90
344.16
EV-1
343.89
EV-8
GM07561-41-2

water table well closest to the irrigation well, recovered from the effects of irrigation pumping after approximately three months (Figure 4).

Using wells EV-10 and EV-8, which are parallel to the groundwater flow direction, the minimum horizontal hydraulic gradient observed during the monitoring period was 3×10^{-4} and the maximum value observed was 7×10^{-4}. Determination of the magnitude of the vertical hydraulic gradient (less than 3×10^{-4}) was limited by instrument sensitivity.

Hydraulic conductivity was estimated from slug tests performed on three wells, EV-12, EV-14, and EV-15 (Table 1). Three slug tests were conducted on each of the two wells, EV-12 and EV-14, and two slug tests were conducted on well EV-15.

Table 1. Hydraulic conductivity based on slug test results - January 30, 1992 (Appendix VI).

SLUG TEST #	DEPTH[1] (metres)	HYDRAULIC CONDUCTIVITY (K) (metres/second)
EV-12-1	17.7-18.5	5.9×10^{-5}
EV-12-2	17.7-18.5	5.6×10^{-5}
EV-12-3	17.7-18.5	5.6×10^{-5}
EV-14-1	11.5-12.3	4.6×10^{-4}
EV-14-2	11.5-12.3	4.2×10^{-4}
EV-14-3	11.5-12.3	4.3×10^{-4}
EV-15-1	8.5-9.3	2.9×10^{-4}
EV-15-2	8.5-9.3	2.8×10^{-4}

[1]screened interval below ground surface (water table at 4.58 m)

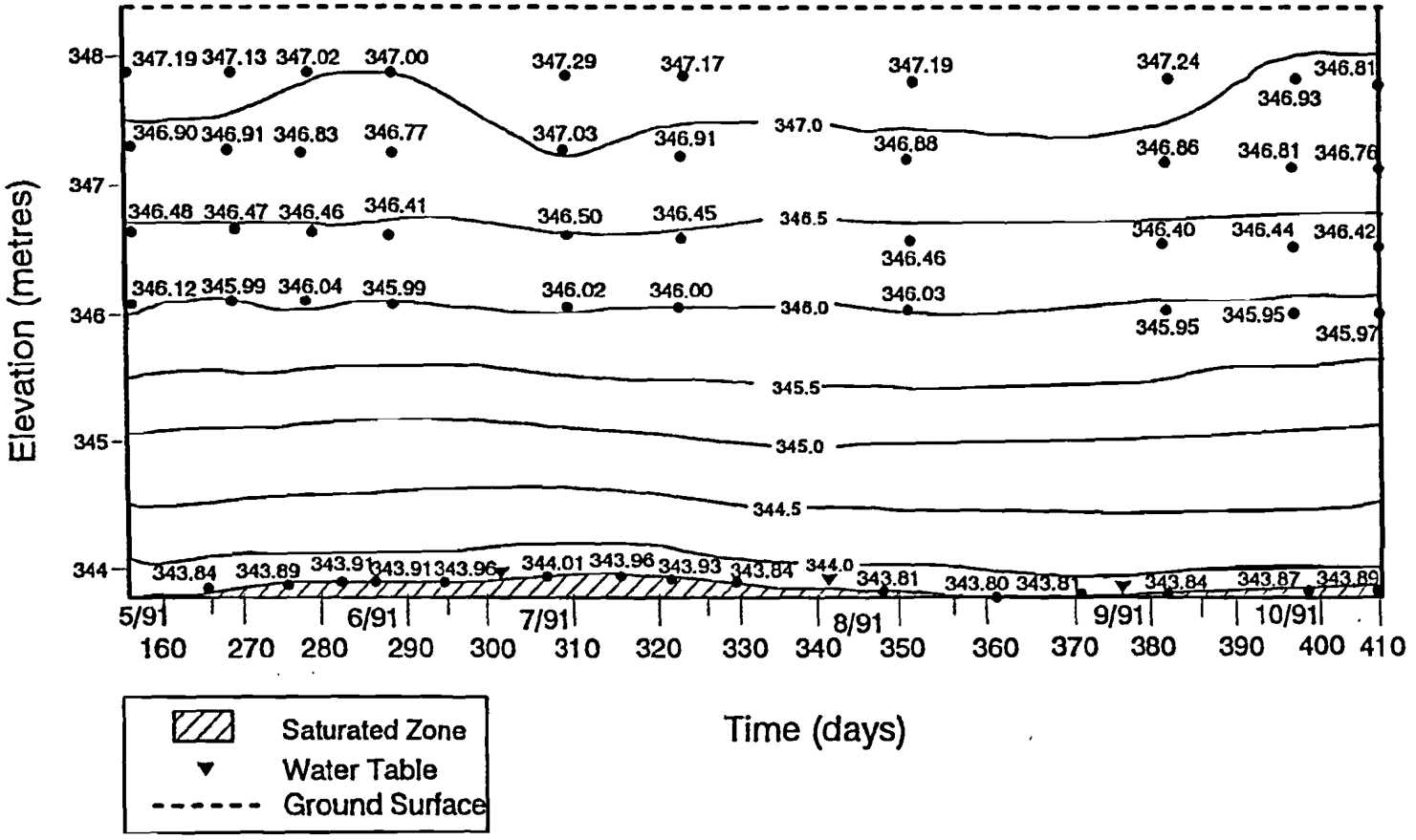
Hydraulic conductivities obtained from wells EV-14 and EV-15 appear to be more representative of the hydraulic conductivity of the aquifer in general because well EV-12 was completed near the bottom of the aquifer where a higher-than-average content of clay-size material was present.

For comparison, hydraulic conductivity was estimated from particulate distribution data (Appendix XII) obtained from sieve and hydrometer analysis of core samples collected during well installations (Table 2). Hydraulic conductivities calculated for each 0.6 metre interval compare favorably with those values obtained from the slug tests. Based on these results, hydraulic conductivity data from slug tests performed on wells EV-14 and EV-15 appear to be more representative of the aquifer.

Using the range of values estimated for the hydraulic gradient and the hydraulic conductivity and a porosity of 0.2, the average groundwater velocity ranges from 4.2×10^{-7} to 1.6×10^{-6} metres/second, or approximately 13 to 50 metres/year.

Unsaturated-zone instrumentation included tensiometers and neutron probe access tubes. Tensiometers were used to estimate the hydraulic head in the unsaturated zone with data (Appendix IV) collected only during the 1991 summer field season to avoid freezing and instrument breakage. A time-depth plot of hydraulic heads (Figure 10) indicates a

Figure 10. Time versus depth plot of hydraulic heads in the unsaturated zone.


Elevation (metres)
348
347
346
345
344
347.19 347.13 347.02 347.00 347.29 347.17 347.19 347.24 346.81
346.93
346.90 346.91 346.83 346.77 347.03 346.91 347.0 346.88 346.86 346.81 346.76
346.48 346.47 346.46 346.41 346.50 346.45 346.5 346.40 346.44 346.42
346.46
346.12 345.99 346.04 345.99 346.02 346.00 346.0 346.03 345.95 345.95 345.97
345.5
345.0
344.5
343.84 343.89 343.91 343.91 343.96 344.01 343.96 343.93 343.84 344.0 343.81 343.80 343.81 343.84 343.87 343.89
5/91
6/91
7/91
8/91
9/91
10/91
160 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410
Time (days)
Saturated Zone
Water Table
Ground Surface

strong downward gradient at the location where the tensiometers were installed (well nest EV-11 to 15).

Table 2. Hydraulic conductivity calculated from particulate size distribution data.

DEPTH[1] (metres)	PARTICLE DIAMETER[2] (millimetres)	HYDRAULIC CONDUCTIVITY (metres/second)
0.0-0.6	0.13	1.7×10^{-4}
0.6-1.8	0.16	2.6×10^{-4}
1.8-2.4	0.21	4.4×10^{-4}
2.4-3.0	0.14	2.0×10^{-4}
3.0-3.7	0.13	1.7×10^{-4}
3.7-4.3	0.14	2.0×10^{-4}
4.3-4.9	0.21	4.4×10^{-4}
4.9-5.5	0.27	7.3×10^{-4}
5.5-6.1	0.22	4.8×10^{-4}
6.1-6.7	0.20	4.0×10^{-4}
6.7-7.3	0.22	4.8×10^{-4}
7.3-7.9	0.20	4.0×10^{-4}
7.9-8.5	0.23	5.3×10^{-4}
8.5-9.1	0.24	5.8×10^{-4}
9.1-9.8	0.22	4.8×10^{-4}
9.8-11.0	0.20	4.0×10^{-4}
11.0-11.6	0.21	4.4×10^{-4}
11.6-12.2	0.22	4.8×10^{-4}
12.2-12.8	0.18	3.2×10^{-4}
12.8-13.4	0.17	2.9×10^{-4}
13.4-14.0	0.18	3.2×10^{-4}
14.0-14.6	0.25	6.3×10^{-4}
14.6-15.2	0.24	5.8×10^{-4}
15.2-15.9	0.21	4.4×10^{-4}
15.9-17.0	0.11	1.2×10^{-4}
17.1-17.7	0.12	1.4×10^{-4}
17.7-18.3	0.13	1.7×10^{-4}
18.3-18.9	0.14	2.0×10^{-4}
18.9-19.5	0.04	1.6×10^{-5}

[1]below ground surface
[2]particle diameter at 10 percent passing

Neutron probe measurements near the tensiometer nest coincided with tensiometer readings. Data collected with the neutron probe were used to determine the vertical moisture profile of the sediments (Appendix V). Moisture content versus depth curves prepared for different dates (Appendix V) do not indicate groundwater recharge other than by snowmelt in the spring.

Hydrogeochemistry

Water-quality data were collected on selected wells sampled in October 1990, May and September 1991, and January 1992 (Appendix VII). The purpose of this sampling and analysis was to determine the composition of water at the site. The five-well nest (January 22, 1992) on the east-central side of the site produced calcium-bicarbonate-type water with an increase in sulfate with depth (Table 3). Conductivity varied from approximately 0.5 microsiemens at the water table to 1.0 microsiemens in the deepest well, reflecting an increase in total dissolved solids.

Nitrogen

Nitrate concentrations were determined for all water-table wells at the site (EV-1,3,8,10,13,16) in addition to the nested wells EV-11 to 15 (Appendix VIII). Nitrate was

present in all of the water table wells except for EV-3, which is the monitoring well closest to the irrigation well.

For wells EV-11 to 15, nitrate was detected in only the two shallow wells and nitrite was not detected in any of the wells (Table 3). Ammonia was not detected in the two shallow wells and was less than 1 mg/l in the deeper wells.

Table 3. Selected water quality data for well nest EV-11 to 15 (January 22, 1992).

Parameter	Units	EV-13	EV-11	EV-15	EV-14	EV-12
Depth[1]	m	1.0	2.5	4.3	7.3	13.6
pH		7.34	7.50	7.55	7.05	7.33
Cond.	mS	0.46	0.38	0.43	0.86	0.96
HCO_3 Alk.	mg/L	226	236	243	346	550
CO_3 Alk.	mg/L	0	0	0	0	0
Calcium	mg/L	64	46	50	130	160
Magnesium	mg/L	26	18	17	43	41
Sodium	mg/L	11	26	34	51	57
Potassium	mg/L	3.6	5.3	6.3	7.1	10.0
Iron	mg/L	<0.2	<0.2	6	12	1.3
Manganese	mg/L	<0.1	1.2	0.9	1.6	0.8
Sulfate	mg/L	14	18	43	240	190
Chloride	mg/L	5.9	3.7	8.7	28	24
TOC	mg/L	30	37	30	38	35
Nitrate[2]	mg/L	15.8	3.4	<1	<1	<1
Nitrite	mg/L	<1	<1	<1	<1	<1
Ammonia	mg/L	<0.05	<0.05	0.22	0.37	0.83
Diss. Oxy.	mg/L	5.71	0.45	0.42	0.39	0.37
Redox Pot.	mV	178	158	-73	-75	-15

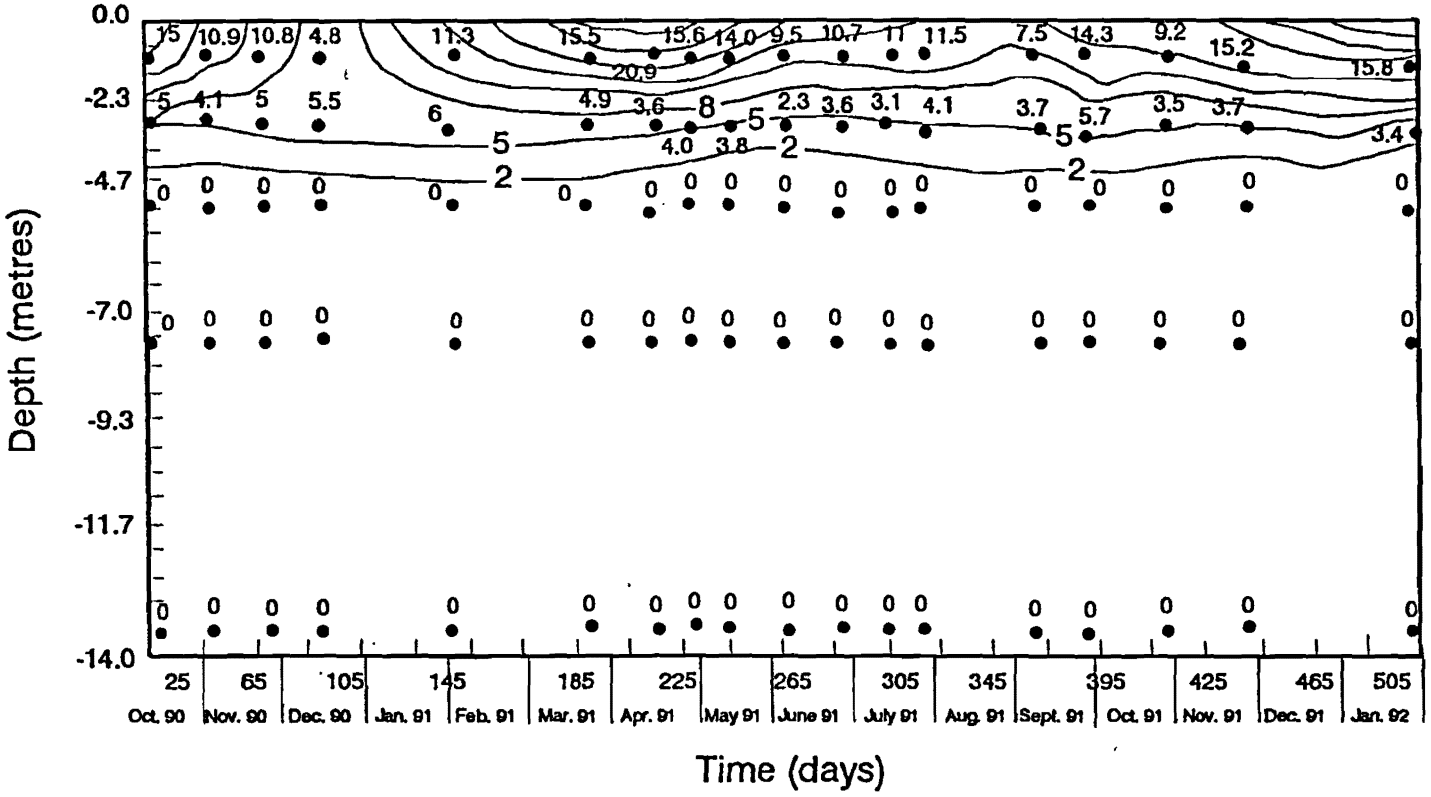
[1]depth of midpoint of screened interval below water table
[2]as nitrate nitrogen

A time-depth plot of nitrate-nitrogen concentrations shows concentrations ranging from a maximum of 20.9 mg/L in the water table well to less than 1 mg/L in the deeper wells for nested wells EV-11 to 15 (Figure 11). Nitrate-nitrogen concentrations in the water table well (EV-13) ranged from 20.9 to 4.8 mg/L. This well is screened from the water table to approximately 1.5 metres below the water table. For most of the monitoring period, nitrate-nitrogen concentrations exceeded the USEPA maximum concentration level of 10 mg/L for drinking water standards (Code of Federal Regulation, 1990) in this well. The maximum nitrate-nitrogen concentration (20.9 mg/L) was detected in the spring of 1991.

Concentrations of nitrate nitrogen between 6.0 and 2.3 mg/L were detected in well EV-11, which is screened from approximately 1.5 to 3.0 metres below the water table. In wells screened at depths greater than this, nitrate was not detected. This pattern was consistent for all well nests sampled.

During the entire monitoring period (October 1, 1990, through January 21, 1992), no nitrate was detected in EV-3. Consequently, additional water quality sampling and analysis (Appendix VII) were performed to determine if irrigation pumping was responsible for the observation. No nitrate was detected in the water table well EV-3 during this sampling (Table 4).

Figure 11. Time versus depth plot of nitrate concentrations in the saturated zone (Well nest EV-11 to 15).


Depth (metres)
0.0
-2.3
-4.7
-7.0
-9.3
-11.7
-14.0
25
65
105
145
185
225
265
305
345
395
425
465
505
Oct. 90
Nov. 90
Dec. 90
Jan. 91
Feb. 91
Mar. 91
Apr. 91
May 91
June 91
July 91
Aug. 91
Sept. 91
Oct. 91
Nov. 91
Dec. 91
Jan. 92
Time (days)

Major cations/anions

Analyses from January 1992 (Table 4) show less vertical contrast in water chemistry near the irrigation well (EV-3 to 5) than at nested wells EV-11 to 15 (Table 3). In addition, much larger concentrations of the major cations and anions are present near the water table (EV-3). The

Table 4. Selected water quality data for well nest EV-3 to 5 (January 22, 1992).

Parameter	Units	EV-3	EV-5	EV-4
Depth[1]	m	1.3	3.8	12.1
pH		7.10	7.05	7.15
Conductivity	mS	0.59	0.70	1.01
HCO_3 Alk.	mg/l	348	412	510
CO_3 Alk.	mg/l	0	0	0
Calcium	mg/l	79	100	200
Magnesium	mg/l	37	39	46
Sodium	mg/l	36	43	50
Potassium	mg/l	7.3	7.8	7.8
Iron	mg/l	3.7	8.4	6.0
Manganese	mg/l	1.4	1.5	0.9
Sulfate	mg/l	97	120	280
Chloride	mg/l	11	18	31
TOC	mg/l	38	39	49
Nitrate[2]	mg/l	<1	<1	<1
Nitrite	mg/l	<1	<1	<1
Ammonia	mg/l	0.07	0.23	0.69
Redox Potential	mV	-11	-86	-39

[1]depth of midpoint of screened interval below water table
[2]as nitrate nitrogen

concentration of sulfate, for example, is 97 mg/l in the water table well EV-3 and only 14 mg/l in water table well EV-13.

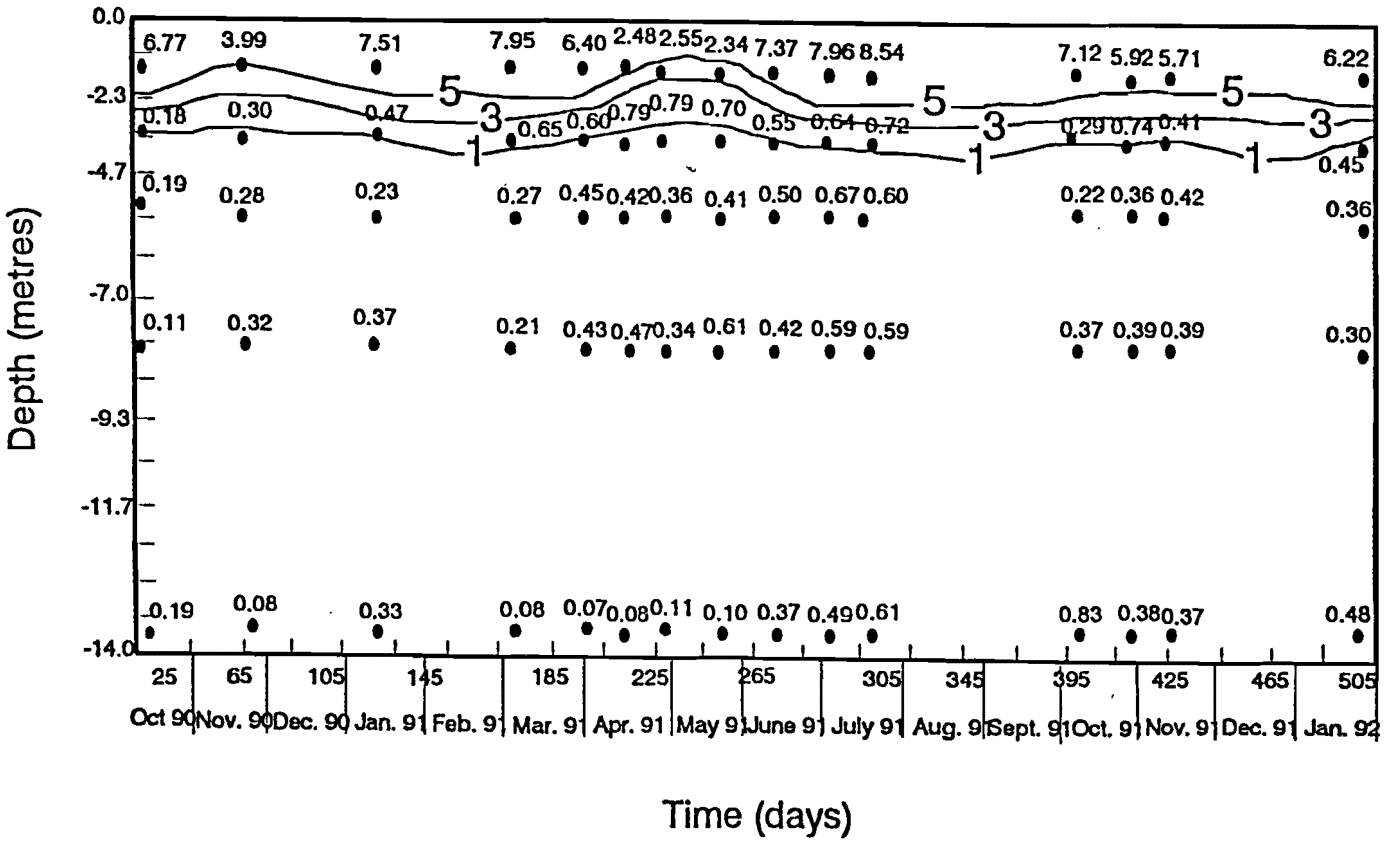
Iron and manganese were detected in all three wells, EV-3 to 5, and the redox potential was comparable to that of the deeper groundwater zones at nested wells EV-11 to 15.

Dissolved oxygen

Field-dissolved-oxygen readings (wells EV-11 to 15) were made in conjunction with nitrate sampling (Appendix IX). Dissolved oxygen concentrations ranged from near saturation to 2.34 mg/L in the water table well (EV-13) and were less than 1 mg/L in the deeper wells during the monitoring period (Figure 12). Low dissolved oxygen concentrations corresponded to reduced concentrations of nitrate. Based on these results, it appears that the most active zone of denitrification is between 1.5 and 3.0 metres below the water table. The lengths of the screened sections for these two wells, however, does not allow this zone to be delineated further.

Lower nitrate concentrations observed in water table well EV-13 during the monitoring period were associated with lower dissolved oxygen concentrations. This would suggest that the zone of denitrification varies in depth through time. Water recharged to the water table would be expected to have higher dissolved oxygen concentrations which would

Figure 12. Time versus depth plot of dissolved oxygen concentrations in the saturated zone (Well nest EV-11 to 15).


Depth (metres)
0.0
-2.3
-4.7
-7.0
-9.3
-11.7
-14.0
6.77 3.99 7.51 7.95 6.40 2.48 2.55 2.34 7.37 7.96 8.54 7.12 5.92 5.71 6.22
5
3
1
0.18 0.30 0.47 0.65 0.60 0.79 0.79 0.70 0.55 0.64 0.72 0.29 0.74 0.41 0.45
0.19 0.28 0.23 0.27 0.45 0.42 0.36 0.41 0.50 0.67 0.60 0.22 0.36 0.42 0.36
0.11 0.32 0.37 0.21 0.43 0.47 0.34 0.61 0.42 0.59 0.59 0.37 0.39 0.39 0.30
0.19 0.08 0.33 0.08 0.07 0.08 0.11 0.10 0.37 0.49 0.61 0.83 0.38 0.37 0.48
25 65 105 145 185 225 265 305 345 395 425 465 505
Oct 90 Nov. 90 Dec. 90 Jan. 91 Feb. 91 Mar. 91 Apr. 91 May 91 June 91 July 91 Aug. 91 Sept. 91 Oct. 91 Nov. 91 Dec. 91 Jan. 92
Time (days)

inhibit nitrate reduction and would also provide a source of nitrate.

Redox potential (Eh)

Of the three redox zones suggested to exist in groundwater flow systems (Champ et al., 1979), two and possibly three of these redox zones are present at the Elk Valley site. The first and commonly the shallowest of these zones is characterized by the presence of oxygen and nitrate. Nitrate was present above detection limits (1 mg/L as NO_3-N) in the upper 3 metres of the saturated zone at the location of nested wells EV-11 to 15, and oxygen was near saturation in the upper 1.5 metres.

The second redox zone is the iron-manganese zone (Champ et al., 1979) and is characterized by a lack of oxygen and nitrate, and the presence of iron and manganese. Iron and manganese were found in detectable concentrations at all depths greater than three metres below the water table (Table 3).

The third redox zone (sulfide zone) is characterized by the reduction of sulfate to sulfide (Champ et al., 1979), which may be present as hydrogen sulfide or form a precipitate such as iron sulfide. Although there is a decrease in sulfate (Table 3) from wells EV-14 to EV-12, sulfide was not detected and there was insufficient evidence to indicate biological sulfate reduction.

TOC/BOD

Total organic carbon (TOC), commonly used to indicate the potential for denitrification, varied from 30 to 38 mg/L in wells EV-11 to 15 (Table 3). To obtain data on the biodegradable organic carbon at different levels in the aquifer, 5-day biological oxygen demand (BOD) tests were performed on samples collected from EV-11 to 15 on June 29, 1992 (Table 5). BOD was below the detection limit in the water table well EV-13, and between 4 and 6 mg/l at greater depths. No difference was observed in BOD between filtered and unfiltered samples although TOC was greater in the unfiltered samples.

Table 5. BOD and TOC concentrations for well nest EV-11 to 15 (June 29, 1992).

Parameter	Units	EV-13	EV-11	EV-15	EV-14	EV-12
Depth	m	1.0	2.5	4.3	7.3	13.6
BOD[1]	mg/L	ND[3]	3	5	5	6
BOD[2]	mg/L	ND	3	5	5	5
TOC[1]	mg/L	28	35	35	37	44
TOC[2]	mg/L	43	40	40	48	78

[1]filtered with a 0.45 micron filter
[2]unfiltered
[3]not detected

Trace metals

Samples were collected and analyzed for selected trace metals (Appendix XI) at three times during the study period

(October 1990, and May and June 1991). None of the trace metals analyzed exceeded the current maximum concentration levels (MCLs) for USEPA drinking water standards (Code of Federal Regulations, 1990). The USEPA, however, is reviewing the MCL for arsenic and is expected to lower the current MCL of 0.05 mg/l to 0.002 mg/l (Pontius, 1992). The detection limits for arsenic in this study varied from 0.003 to 0.010 mg/l. At least 10 of the 36 samples analyzed had arsenic concentrations above the detection limit and the proposed standard.

Tritium

Three wells in nest EV-11 to 15 and all three wells in nest EV-3 to 5 were sampled to compare the vertical distribution of tritium. Tritium concentrations (reported as TU, where a tritium unit is one tritium atom per 10^{18} hydrogen atoms) can be indicative of groundwater age and groundwater flow path. Tritium concentrations (Table 6) were found to decrease with depth for well nest EV-11 to 15, which indicates groundwater residence increases towards the bottom of the aquifer. Samples collected from nested wells EV-3 to 5, however, had tritium concentrations of about 42 tritium units (TU). These concentrations, indicative of tritium levels in precipitation (Solomon et al., 1992), suggest recent recharge of groundwater.

Table 6. Tritium concentrations in well nests EV-11 to 15 and EV-3 to 5.

Well Number	Depth[1] m	Tritium Units TU
EV-13	1.0	27.2 ± 1.3
EV-14	7.3	2.2 ± 0.5
EV-12	13.6	<0.8 ± 0.5
EV-3	1.3	41.2 ± 2.8
EV-5	3.8	42.0 ± 2.9
EV-4	12.1	42.7 ± 2.9

[1]depth of midpoint of screened interval below water table

Microbiology

Microbiological sampling was performed to determine if bacteria and, in particular, denitrifying bacteria are present in the aquifer. In addition, because nitrate is stratified within the aquifer, the vertical distribution of denitrifying bacteria could be expected to correlate with nitrate concentrations. Denitrifying bacteria were found to be present at all sampled intervals within the aquifer (Table 7). The results indicate, however, an increase in the number of denitrifiers with increasing depth. Although the results indicate the approximate number of denitrifiers

present within the sampled intervals, they do not provide information on the rate of denitrification or the activity of the organisms.

Sampling and analyses were also performed to determine if autotrophic denitrifiers were present. Nitrate and nitrite analyses, however, were problematic because of interfering ions in the media. Microscopic evaluation demonstrated the presence of very small pleomorphic rods, not typical of Thiobacillus denitrificans. Several types of autotrophic denitrifiers are known, however, and revised procedures are required to determine if autotrophic denitrifiers are present.

Table 7. Total bacteria counts and denitrifier population data for five well nest (EV-11 to 15).

Well Number	Depth[1] m	Total Bacteria Counts CFU[2]/ml	Denitrifiers MPN[3]/ml
EV-13	1.0	2.8×10^5	7.0×10^2
EV-11	2.5	1.4×10^5	3.3×10^2
EV-15	4.3	3×10^4	7.9×10^3
EV-14	7.3	3×10^4	1.5×10^3
EV-12	13.6	9×10^4	3.3×10^4

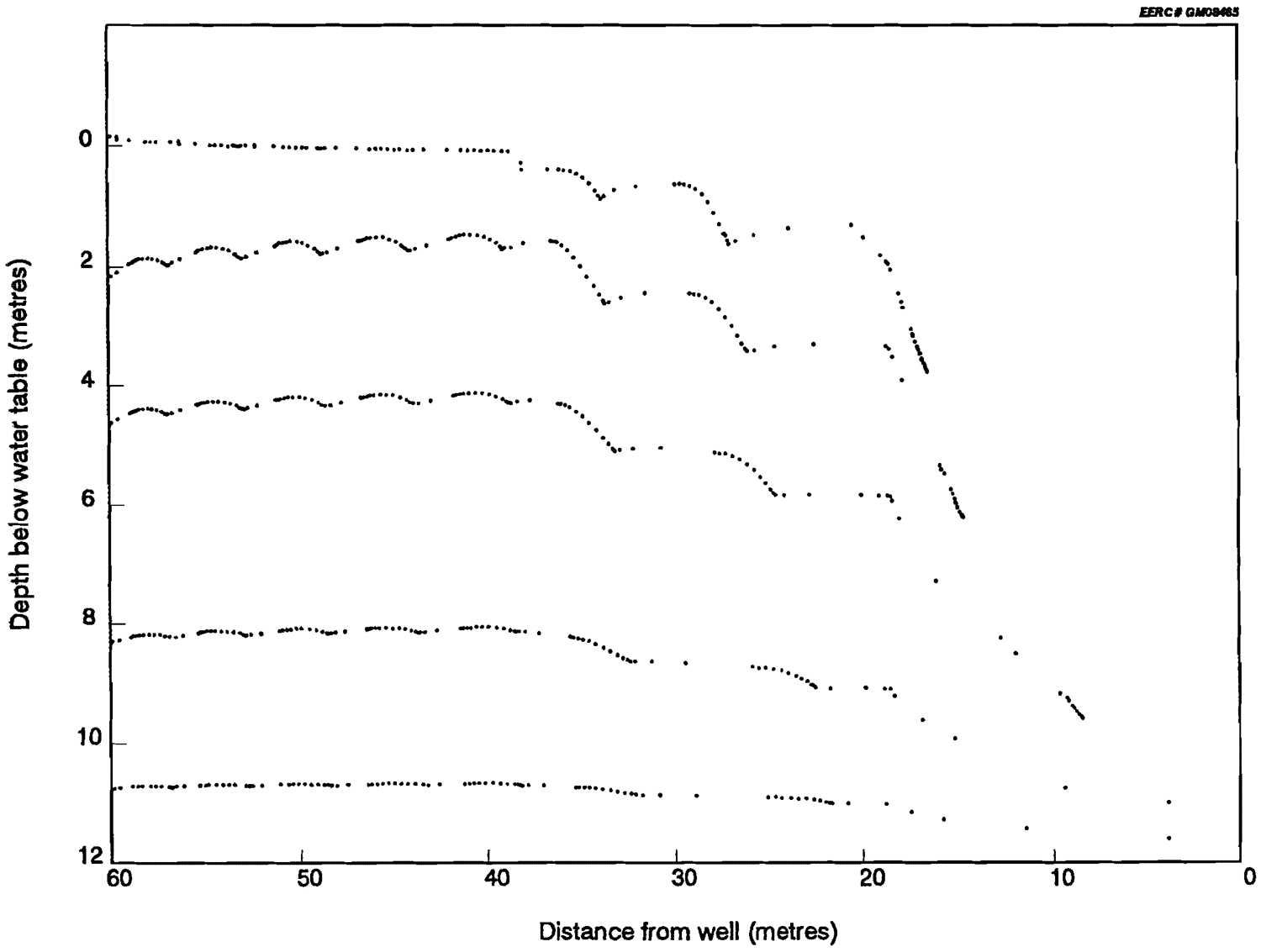
[1]Depth at middle of screened interval below water table.
[2]Colony forming units
[3]Most probable number

Numerical Modeling

MODFLOW was used to simulate the hydraulic heads resulting from intermittent pumping of an irrigation well at the Elk Valley site. A grid size of 627,581 square metres and 12.2 metres thick was used in the simulation. Ten layers, each 1.2 metres thick, were used to indicate hydraulic heads within the aquifer. The irrigation well, screened across the bottom five layers, had a discharge rate of 3270.6 cubic metres/day. Sixteen stress periods used during the simulation consisted of eight two-day pumping periods followed by a five-day recovery period each, with the exception of the final recovery period which was 300 days. Output from the MODFLOW simulation (Appendix XIII) consists of hydraulic heads for row 13, layers 1 to 10, columns 1 to 13 of the grid. Output is for the end of each stress period and for the ten time steps in the final recovery period.

A groundwater path and travel-time simulator, PATH3D, was used to track particle movement in response to the changes in hydraulic head resulting from intermittent irrigation pumping (Figure 13). In the upper part of the aquifer, particles followed a sine-wave flow pattern with upward movement during periods of irrigation pumping and downward movement during periods of recovery. In addition, there was an overall upward movement of particles in this

Figure 13. Particle flow paths resulting from intermittent irrigation pumping.


EERC # GM08465
Depth below water table (metres)
0
2
4
6
8
10
12
60
50
40
30
20
10
0
Distance from well (metres)

part of the aquifer at distances greater than 30 metres from the irrigation well.

Within 30 metres of the irrigation well, there was a strong downward movement of particles within the aquifer. This downward movement of particles was observed even during periods of recovery because of large vertical hydraulic head differences induced by irrigation pumping.

DISCUSSION

Denitrification

All requirements for denitrification at the Elk Valley study site were met. These requirements include the presence of nitrate or nitrite, dissolved oxygen concentrations below 0.5 to 1.5 mg/L, dissolved organic carbon concentrations above 10 mg/L, and the presence of denitrifying bacteria.

Nitrate was found to be present at the Elk Valley study area but was not detected during the monitoring period at depths greater than three metres below the water table (Appendix VIII). This stratification of nitrate has been noted by other researchers (Gillham and Cherry, 1978). The highest nitrate concentrations found during the study period were in the water table well (Figure 11), which was screened from the water table to approximately 1.5 metres below the water table. For much of the study period, these nitrate levels exceeded the USEPA maximum concentration of 10 mg/L for drinking water standards (Code of Federal Regulation, 1990), and corresponded with dissolved oxygen concentrations

near saturation. In the monitoring well screened from 1.5 to 3.0 metres below the water table, nitrate levels decreased to approximately one-half of the concentration noted in the water table well (Figure 11). This decrease in nitrate concentrations corresponded with a decrease in dissolved oxygen (Figure 12). Because dissolved oxygen was below that required for denitrification and nitrate levels decreased, it is likely that this well is within the most active zone of denitrification.

Dissolved organic matter concentrations at the Elk Valley site were well above those levels normally required for denitrification (Table 5). To estimate the biodegradable organic carbon present, biological oxygen demand (BOD) tests were performed. BOD data (Table 5) indicate that nitrate and oxygen are not reduced near the water table because of insufficient biodegradable organic carbon. In a study of the Fordville aquifer in Walsh County of eastern North Dakota, similar results were obtained and nitrate, dissolved oxygen, and BOD were related to land use (Gerla et al., 1992).

If biodegradable organic matter is depleted near the water table, then the source of biodegradable organic matter at deeper levels within the aquifer is unknown. Starr and Gillham (1989), in a study of two aquifers in Ontario, Canada, indicate that the source of organic matter is in the vadose zone and that organic matter present in the aquifers

varies with depth from the ground surface to the water table. They found that under deep water-table conditions, insufficient organic matter was present to support denitrification and that nitrate contamination of the aquifer resulted.

If the source of organic matter is the vadose zone, hydrological conditions may control the transport of organic matter to the saturated zone at the Elk Valley site. Although there is a strong downward hydraulic gradient in the unsaturated zone (Figure 10), soil moisture estimates (Appendix V) indicate recharge does not occur except possibly in the spring at the study area. Also, irrigation does not appear to result in recharge over the general land surface. This indicates that evapotranspiration exceeds input from irrigation and precipitation at this location and that irrigation practices do not induce recharge of groundwater. Recharge of groundwater would occur only during significant precipitation events or be localized to topographical lows where the water table is closer to the ground surface.

Other potential sources of organic matter include organic carbon present in the mineral sediments and the biochemical alteration of less degradable complex organic compounds to simpler, degradable products which can be used more efficiently by the denitrifying organisms. Because this biochemical conversion of complex organic compounds

would be slow, the limiting factor for denitrification may be the rate of biochemical alteration.

The occurrence of bacteria in shallow groundwater systems is well established (Lowrance and Pionke, 1989). The presence of denitrifiers at the Elk Valley site was confirmed from the microbiological testing. Denitrifiers were found at all sampled depths within the aquifer and tended to increase with depth in the aquifer (Table 7). The highest levels of denitrifiers were not found in the most active zone of denitrification. Simply quantifying the number of denitrifiers or noting the presence of denitrifying genera, however, is not an indicator of denitrifying activity. Samples collected for microbiological analyses were of groundwater and did not include aquifer sediments. These samples may not indicate the total denitrifying population present in the aquifer because attached-growth organisms would be excluded by the sampling technique.

The presence of autotrophic denitrifiers could indicate the potential for denitrification in the absence of organic carbon and provide insight to the geochemical evolution of groundwater in regard to sulfate. Because bacteria were found at all depths within the aquifer and sulfate concentrations increased with depth (Table 3), an attempt was made to determine the presence of autotrophic denitrifiers. The media of Hutchinson et al. (1967) were

used but interfering ions affected the nitrate analyses and did not allow determination of nitrate uptake which would have indicated the presence of autotrophic denitrifiers.

Effects of Irrigation

The increase in irrigation pumping from the Elk Valley aquifer has raised concerns over the depletion of water in the aquifer. Long-term monitoring of water levels in the aquifer is required to assess the effects of irrigation on groundwater in the aquifer, including the potential for depletion of groundwater supplies. Water level data presented in Figure 3, however, indicate that during the monitoring period, irrigation pumping did not have a long-term affect on the water table.

Nitrate sampling and analysis at the Elk Valley site indicated the presence of nitrate in water table wells throughout the monitoring period with the exception of EV-3, which is the water table well closest to the irrigation well. Because nitrate was not detected in this water table well during the monitoring period, additional characterization of the three-well nest (EV-3 to 5) was undertaken.

Comparison of the results for samples collected and analyzed from well nest EV-3 to 5 (Table 4) with those for

well nest EV-11 to 15 (Table 3) indicate less vertical contrast in water chemistry near the irrigation well. In addition, much larger concentrations of the major cations and anions are present near the water table. Tritium analyses indicate a decrease in tritium concentrations with depth at nested wells EV-11 to 15 (Table 6). At the location of well nest EV-3 to 5, however, there is no vertical change in tritium and concentrations are representative of recently recharged groundwater.

Numerical modeling of groundwater flow and particle movement within the aquifer indicates particles followed a sine-wave flow pattern with upward movement during periods of irrigation pumping and downward movement during periods of recovery in the upper part of the aquifer. In addition, there is an overall upward movement of particles in this part of the aquifer at distances greater than 30 metres from the irrigation well. This observation may explain the low vertical contrast in water chemistry near the irrigation well when compared to nested wells EV-11 to 15. Around the irrigation well there is a strong downward movement of particles even during periods of recovery (Figure 13) due to the vertical contrast in hydraulic heads (Appendix XIII). This would account for the high tritium concentrations observed in the lower part of the aquifer.

Nitrate contaminant plumes downgradient from irrigation wells have been noted by Hammond and Goodman (1992).

Irrigation-induced downward movement of nitrate and dissolved oxygen could result in nitrate contaminant plumes that would extend to the depth of the screened interval of the irrigation well. If sufficient biodegradable organic carbon were not available within the aquifer to reduce dissolved oxygen and allow denitrification, nitrate contamination of the aquifer could result.

Autotrophic denitrification could also play a major role in reducing the potential for nitrate contamination resulting from irrigation pumping. If sufficient biodegradable carbon is not available at depth within the aquifer to support heterotrophic denitrification but aquifer sediments contain inorganic compounds suitable for oxidation and supplying the energy requirements of autotrophs, denitrification by autotrophic bacteria could control nitrate occurrence and contamination.

Future Work

Future research includes the use of indirect techniques such as nitrate/chloride ratios or direct techniques such as ^{15}N-labeled nitrate ratios or the acetylene inhibition method to further identify the role of denitrification at the study site.

Because little information is available on populations of microorganisms or the microbial ecology of aquifers, further work is planned to identify the heterotrophic and autotrophic bacteria responsible for denitrification in the aquifer.

The source of biodegradable organic matter needs to be identified to determine the potential for heterotrophic denitrification and the effect irrigation may have on nitrate contamination of an aquifer. This will be accomplished by a study of hydrological conditions which may control the transportion of organic matter to the saturated zone and by the characterization of organic matter within the saturated zone.

The long-term effects of irrigation on groundwater in the saturated zone will be determined by continued monitoring of groundwater chemistry. The aquifer will be modeled to determine how aquifer properties, screened depth of the irrigation well, and irrigation pumping rate and timing affect groundwater flow and contaminant movement.

CONCLUSIONS

All requirements for denitrification at the Elk Valley study site were met. These requirements include the presence of nitrate or nitrite, dissolved oxygen concentrations below 0.5 to 1.5 mg/L, dissolved organic carbon concentrations above 10 mg/L, and the presence of denitrifying bacteria. Denitrification appears to control nitrate occurrence and distribution in the Elk Valley aquifer.

High concentrations of nitrate associated with dissolved-oxygen concentrations near saturation and the absence of BOD were characteristic of the upper 1.5 metres of the saturated zone at the study site. Reduced nitrate levels at the 1.5 to 3 metre interval, in addition to dissolved-oxygen concentrations of less than 1 mg/L and detectable BOD, indicate this to be the active zone of heterotrophic denitrification.

Biological oxygen demand (BOD) can be used to indicate the presence of biodegradable organic matter and the potential for denitrification by heterotrophic bacteria. The source of biodegradable organic matter observed at

depths greater than the 1.5 metres below the water table is not known but may be explained by hydrogeological conditions responsible for recharge of groundwater or by biochemical alteration of complex organic compounds to simpler biodegradable products within the saturated zone.

The presence of autotrophic denitrification at the Elk Valley site was not established. Autotrophic denitrifiers could indicate the potential for denitrification in the absence of organic matter and provide insight into the geochemical evolution of groundwater regarding sulfate. In addition, the potential for nitrate contamination of an aquifer due to irrigation pumping could be minimized by these denitrifiers.

Intermittent pumping of irrigation wells was found to affect groundwater flow and the vertical displacement of contaminants. Numerical modeling of particle movement indicates a sine-wave path with upward movement during periods of irrigation pumping and downward movement during periods of recovery in the upper part of the aquifer. In addition, overall upward movement of particles occurred at distances greater than 30 metres from the irrigation well in the upper part of the aquifer. Near the irrigation well, there was a strong downward movement of particles even during periods of recovery because of the vertical contrast in hydraulic heads resulting from irrigation pumping.

APPENDICES

APPENDIX I

CORE DESCRIPTIONS FOR TEST HOLE EV-12

Appendix I

Core descriptions are given for test hole EV-12 at the location of well nest EV-11 to 15. The descriptions are based on field observations during drilling operations and on microscopic examination of samples collected with a split-spoon sampler. Mineral percentages were estimated visually during the microscopic examination of the samples. Dilute hydrochloric acid was used to indicate the presence of limestone grains.

Depth (metres)	Descriptions
0 - 0.6	Black, organic-rich, sandy topsoil. Angular to subangular quartz grains. Some plant fragments.
0.6 - 1.2	Brown, organic-rich, clayey quartz sand. Angular to subangular quartz grains.
1.2 - 1.8	Brown, medium-grained, poorly-sorted, angular to subrounded sand. Quartz - 60%, dolomite - 10%, other* - 30%.
1.8 - 2.4	Brown, coarse-grained, poorly-sorted, subangular to rounded sand. Dolomite - 60%, quartz - 35%, other - 5%.
2.4 - 3.0	Brown, medium- to very fine-grained, poorly-sorted sand. Dolomite - 65%, quartz - 30%, other - 5%. Dolomite grains subrounded to rounded. Quartz grains range from fine to very-fine sized. Some iron-oxide staining.
3.0 - 3.7	Brown, medium- to fine-grained, poorly-sorted sand. Quartz - 60%; dolomite - 30%; other - 10%. Quartz grains angular to subrounded and dolomite grains subangular to rounded. Some iron-oxide staining.
3.7 - 4.3	Brown, medium-grained, poorly-sorted sand, Quartz - 60%, dolomite - 30%, shale - 10%. Quartz grains angular to subrounded, dolomite grains subrounded to rounded, and shale grains subrounded. Some iron- oxide staining.
4.3 - 4.9	Brown, coarse- to medium-grained, poorly-sorted sand. Dolomite - 70%, quartz - 20%, other - 10%. Dolomite grains subrounded and quartz grains subangular to subrounded. Some feldspar grains present, also.
4.9 - 5.5	Brown, coarse- to medium-grained, poorly-sorted sand. Dolomite - 60%, quartz - 30%, feldspar - 10%. Dolomite grains subrounded and quartz grains angular to subrounded.
5.5 - 6.1	Brown, coarse- to medium-grained, poorly-sorted sand. Dolomite - 75%, quartz - 15%, feldspar - 5%, other - 5%. Dolomite-grains

subrounded and quartz grains angular to subrounded.

6.1 - 6.7	Brown, coarse- to medium-grained, poorly-sorted sand. Dolomite - 70%, quartz - 20%, other - 10%. Dolomite grains subrounded and quartz grains angular to subrounded.
6.7 - 7.3	Brown, coarse- to medium-grained, poorly-sorted, sand. Dolomite - 60%, quartz - 30%, other - 10%. Dolomite grains subrounded and quartz grains very angular to subangular.
7.3 - 7.9	Brown, coarse- to medium-grained, moderately-sorted sand. Quartz - 80%, dolomite/limestone - 15%, other - 5%. Quartz grains angular to subrounded and dolomite/limestone grains subangular to subrounded. Some coal inclusions.
7.9 - 8.5	Gray, coarse- to medium-grained, poorly-sorted sand. Shale - 70%, quartz - 20%, other - 10%. Shale grains rounded and quartz grains angular to subrounded. Some coal inclusions.
8.5 - 9.1	Gray, coarse- to medium-grained, moderately-sorted sand. Shale - 50%, quartz - 30%, dolomite/limestone - 15%, other - 5%. Shale grains rounded and quartz grains angular to subrounded.
9.1 - 9.8	Gray, coarse- to medium-grained, moderately-sorted sand. Quartz - 40%, shale - 40%, other - 20%. Shale grains rounded and quartz grains angular to rounded.
9.8 - 10.4	Gray, coarse- to medium-grained, poorly-sorted sand. Shale - 65%, quartz - 30%, other - 5%. Shale grains rounded and quartz grains angular to rounded.
10.4 - 11.0	Gray, coarse- to medium-grained, poorly-sorted sand, Quartz - 40%, shale - 20%, dolomite/limestone - 20%, other - 20%. Shale grains rounded and quartz grains angular to rounded.
11.0 - 11.6	Gray, medium-grained, fairly well-sorted sand. Quartz - 70%, limestone/dolomite -

	20%, other - 10%. Limestone/dolomite grains subrounded and quartz grains angular to subrounded.
11.6 - 12.2	Gray, coarse- to medium-grained, poorly-sorted sand. Shale - 70%, quartz - 20%, other - 10%. Shale grains rounded to well rounded and quartz grains subangular to rounded.
12.2 - 12.8	Gray, coarse- to medium-grained, poorly-sorted sand. Shale - 60%, quartz - 20%, dolomite/limestone - 15%, other - 5%. Shale grains subrounded to rounded and quartz grains subangular to rounded.
12.8 - 13.4	Gray, very coarse- to medium-grained, very poorly-sorted sand. Shale - 50%, quartz - 30%, dolomite/limestone - 10%, other - 10%. Shale grains subrounded to rounded and quartz grains subangular to rounded.
13.4 - 14.0	Gray, very coarse- to medium-grained, very poorly-sorted sand. Quartz - 60%, shale - 30%, other - 10%. Quartz grains subangular to rounded and shale grains subrounded.
14.0 - 14.6	Gray, very coarse- to medium-grained, very poorly-sorted sand. Shale - 60%, quartz - 30%, other - 10%. Shale grains subrounded to rounded and quartz grains subangular to well rounded.
14.6 - 15.2	Gray, medium-grained, moderately-sorted sand. Shale - 75%, quartz - 20%, other - 5%. Shale grains subangular to subrounded and quartz grains angular to rounded.
15.2 - 15.9	Gray, coarse- to medium-grained, moderately-sorted sand. Shale - 95%, other - 5%. Shale grains subrounded to rounded.
15.9 - 16.5	Gray, fine-grained, well-sorted sand. Shale - 90%, other 5%. Shale grains subangular.
16.5 - 17.7	Gray, fine-grained, well-sorted sand, Shale - 95%, other 5%. Shale grains subangular.

17.7 - 18.3	Gray, medium- to fine-grained, moderately-sorted sand. Shale 95%, other - 5%. Shale grains subangular to rounded.
18.3 - 18.9	Gray, coarse- to medium-grained, poorly-sorted sand. Shale - 95%, other - 5%. Shale grains subangular to rounded. Some coal inclusions.
18.9 - 19.5	Gray, coarse- to medium-grained, poorly-sorted sand. Shale - 80%, other - 20%. Shale grains subangular to rounded.
19.5 - 20.1	Gray, very fine-grained, well-sorted sand. Shale - 80%, other - 20%.
20.1 - 20.7	Gray, clay till with 2" sand layer in lower third of the core.

* Other refers to minor constituents such as feldspar, hornblende, etc.

APPENDIX II

WELL ELEVATION DATA

Appendix II

Well data include the total depth of the well from the top of the casing (TOC), the elevation at TOC, ground surface elevation, bottom of well elevation, screen length, screened interval as elevation, and the midpoint of the screen (elevation) for each of the 18 wells. All values presented are in metres and the datum is sea level.

All wells were installed by hollow-stem auger drilling techniques. Hollow-stem auger size was 10.2 centimetres I.D. by 20.3 centimetres O.D. The sand pack consisted of no. 16 silica sand which was placed from the bottom of the well to approximately 0.4 to 0.6 metres above the well screen. A 0.4 to 0.6 metre seal was placed above the sand pack using 0.6 centimetre bentonite pellets. A grout mixture of six percent (by weight) bentonite powder in Portland cement was used to complete the hole to the ground surface. Concrete pads, approximately 0.6 metres in diameter were placed around 10 centimetre-diameter black-iron casings to protect the wells and to prevent downward movement of water in the vicinity of the well.

Special precautions were taken during the installation of monitoring wells to avoid contamination from drilling or well construction materials. Auger flights were steam cleaned at the site before use to avoid cross contamination between holes. Well screens, casing, couplings, and end caps consisted of 316 stainless steel and were steam cleaned twice before use. All tools used during well installation were also steam cleaned and protective gloves were worn when handling all materials.

Stratigraphic information, including split-spoon samples, were obtained from test holes drilled by rotary-mud techniques. Using these data, well placement depths were determined and holes were drilled using the hollow-stem auger. When desired depths were reached, the screen and casing were inserted into the hollow-stem auger. Well completion using sand, bentonite pellets, and grout was done as auger flights were removed from the hole.

Well	Total Depth* (TOC)**	Elevation (TOC)	Ground Surface (Elev.)	Bottom of Well (Elev.)	Screen Length	Screened Interval (Elev.)	Midpoint of Screen (Elev.)
EV-1	6.10	347.26	346.33	341.16	3.05	341.16-344.21	342.69
EV-2	10.18	347.29	346.33	337.11	0.76	337.11-337.87	337.49
EV-3	8.89	350.07	349.15	341.18	3.05	341.18-344.23	342.71
EV-4	18.45	350.05	349.15	331.60	0.76	331.60-332.36	331.98
EV-5	10.16	350.01	349.15	339.85	0.76	339.85-340.61	340.23
EV-6	19.27	348.56	347.59	329.29	0.76	329.29-330.05	329.67
EV-7	9.08	348.41	347.59	339.33	0.76	339.33-340.09	339.71
EV-8	7.43	348.54	347.59	341.11	3.05	341.11-344.16	342.64
EV-9	19.21	348.73	347.76	329.52	0.76	329.52-330.28	329.90
EV-10	7.47	348.64	347.76	341.17	3.05	341.17-344.22	342.70
EV-11	8.81	349.61	348.57	340.80	1.52	340.80-342.32	341.56
EV-12	19.46	349.54	348.57	330.08	0.76	330.08-330.84	330.46
EV-13	7.37	349.54	348.57	342.17	1.52	342.17-343.69	342.93
EV-14	13.21	349.51	348.57	336.30	0.76	336.30-337.06	336.68
EV-15	10.17	349.48	348.57	339.31	0.76	339.31-340.07	339.69
EV-16	8.02	348.91	348.10	340.89	3.05	340.89-343.94	342.42
EV-17	16.38	348.86	348.10	332.48	0.76	332.48-333.24	332.86
EV-18	9.99	349.03	348.10	339.04	0.76	339.04-339.80	339.42

* All values in meters (Datum - MSL)
** TOC = Top of casing

APPENDIX III

WATER LEVEL ELEVATIONS

Appendix III

Water level readings were obtained with a water level probe accurate to 0.30 centimetres. Water level elevations are reported above mean sea level.

WATER LEVEL ELEVATIONS (metres)

WELL	EV-1	EV-2	EV-3	EV-4	EV-5	EV-6
DATE						
07/26/90	344.09	344.08	343.67	343.68	343.67	343.85
08/01/90	344.06	344.06	343.56	343.56	343.56	343.87
08/30/90	--	--	--	--	--	--
08/31/90	343.97	344.00	--	--	--	343.77
09/06/90	--	--	343.33	343.40	343.34	--
09/12/90	343.96	343.97	343.27	343.30	343.27	343.71
09/26/90	343.90	343.94	343.70	343.72	343.81	343.69
10/01/90	343.89	--	343.73	--	--	--
10/02/90	--	--	--	--	--	--
10/24/90	343.84	343.85	343.77	343.78	343.79	343.66
11/14/90	343.83	343.83	343.80	343.81	343.81	343.62
12/05/90	343.81	343.81	343.80	343.85	343.84	343.61
12/22/91	--	--	--	--	--	--
02/05/91	343.77	343.77	343.77	343.81	343.77	343.57
03/14/91	343.72	343.73	343.74	343.79	343.81	343.56
04/04/91	343.75	343.74	343.80	343.82	343.80	343.56
04/09/91	343.74	343.78	343.84	343.81	343.81	343.55
04/16/91	343.75	343.77	343.80	343.80	343.80	343.58
04/24/91	343.75	343.75	343.81	343.81	343.81	343.56
05/08/91	343.85	343.90	343.84	343.89	343.84	343.57
05/14/91	343.89	343.89	343.88	343.89	343.93	343.60
05/21/91	343.92	343.96	343.93	343.93	343.94	343.64
05/29/91	343.94	343.94	343.99	343.99	343.99	343.67
06/08/91	343.96	344.06	344.02	344.03	344.02	343.72
06/14/91	343.98	343.98	343.75	343.74	343.75	343.74
06/19/91	343.94	344.02	343.96	343.96	344.02	343.75
06/26/91	343.99	343.99	343.95	343.95	343.95	343.77
07/10/91	344.15	344.15	343.98	343.97	344.01	343.82
07/18/91	344.18	344.18	343.65	343.63	343.64	343.87
07/24/91	344.18	344.18	343.66	343.65	343.65	343.87
08/01/91	344.16	344.18	343.45	343.45	343.45	343.84
08/20/91	344.12	344.11	343.68	343.67	343.68	343.77
08/29/91	344.09	344.09	343.64	343.64	343.64	343.74
09/03/91	344.07	344.07	343.50	343.49	343.50	343.73
09/13/91	344.05	344.05	343.80	343.80	343.73	343.70
09/24/91	344.10	344.10	343.85	343.85	343.86	343.70
10/10/91	344.10	344.14	343.90	343.97	343.97	343.74
10/22/91	344.08	344.08	343.96	343.95	343.99	343.74
11/15/91	344.13	344.13	344.02	344.03	344.03	343.78
11/21/91	344.13	344.13	344.05	344.06	344.06	343.80
12/17/91	344.09	344.11	344.09	344.10	344.16	343.84
01/21/92	344.06	344.07	344.09	344.11	344.11	343.85
01/30/92	344.05	344.13	344.09	344.09	344.09	343.84

WATER LEVEL ELEVATIONS (metres)

WELL	EV-7	EV-8	EV-9	EV-10	EV-11	EV-12
DATE						
07/26/90	--	--	--	--	--	--
08/01/90	343.87	343.87	344.24	344.23	--	--
08/30/90	--	--	--	--	343.80	343.75
08/31/90	343.73	343.73	344.07	343.97	--	--
09/06/90	--	--	--	--	--	--
09/12/90	343.74	343.70	344.04	344.00	343.73	343.72
09/26/90	343.66	343.67	343.99	343.98	343.71	343.71
10/01/90	--	--	--	343.99	--	--
10/02/90	--	343.70	--	--	--	343.71
10/24/90	343.62	343.61	344.02	343.88	343.72	343.72
11/14/90	343.60	343.64	344.03	344.03	343.73	343.73
12/05/90	343.61	343.62	344.03	344.02	343.74	343.73
12/22/91	--	--	--	--	343.72	343.71
02/05/91	343.56	343.57	344.00	343.99	343.70	343.70
03/14/91	343.54	343.55	343.89	343.98	343.68	343.67
04/04/91	343.56	--	344.00	343.99	343.70	343.70
04/09/91	343.59	--	344.00	343.99	343.70	343.69
04/16/91	343.56	343.57	344.00	343.99	343.73	343.71
04/24/91	343.56	343.56	344.00	343.99	343.72	343.72
05/08/91	343.57	343.58	344.01	344.01	343.76	343.74
05/14/91	343.61	343.61	344.05	344.05	343.75	343.76
05/21/91	343.65	343.67	344.09	344.09	343.80	343.79
05/29/91	343.68	343.67	344.14	344.14	343.84	343.84
06/08/91	343.71	343.75	344.19	344.18	343.89	343.88
06/14/91	343.75	343.74	344.22	344.21	343.91	343.91
06/19/91	343.80	343.79	344.21	344.09	343.91	343.90
06/26/91	343.77	343.77	344.20	344.20	343.91	343.91
07/10/91	343.85	343.83	344.29	344.28	343.96	343.97
07/18/91	343.88	343.87	344.34	344.33	344.01	344.00
07/24/91	343.88	343.87	344.31	344.27	343.96	343.95
08/01/91	343.91	343.89	344.29	344.27	343.93	343.92
08/20/91	343.78	343.78	344.19	344.18	343.84	343.83
08/29/91	332.78	343.74	344.16	344.16	343.81	343.81
09/03/91	343.73	343.73	344.13	344.12	343.80	343.80
09/13/91	343.71	343.70	344.15	344.15	343.81	343.80
09/24/91	343.71	343.70	344.20	344.20	343.84	343.83
10/10/91	343.73	343.77	344.25	344.25	343.87	343.90
10/22/91	343.79	343.66	344.27	344.27	343.89	343.89
11/15/91	343.79	343.78	344.32	344.31	343.94	343.93
11/21/91	343.81	343.80	344.33	344.33	343.95	343.95
12/17/91	343.84	--	344.35	344.36	344.00	344.00
01/21/92	343.85	343.86	344.34	344.34	344.01	344.01
01/30/92	343.85	343.85	344.32	344.31	344.00	343.99

WATER LEVEL ELEVATIONS (metres)

WELL	EV-13	EV-14	EV-15	EV-16	EV-17	EV-18
DATE						
07/26/90	--	--	--	--	--	--
08/01/90	--	--	--	--	--	--
08/30/90	--	--	--	343.91	343.87	343.88
08/31/90	--	--	--	--	--	--
09/06/90	343.77	343.75	343.75	--	--	--
09/12/90	343.73	343.72	343.72	343.86	343.83	343.84
09/26/90	343.75	343.74	343.70	343.79	343.77	343.82
10/01/90	--	--	--	--	--	--
10/02/90	343.73	343.71	343.71	343.83	--	--
10/24/90	343.74	343.72	343.75	343.78	343.78	343.78
11/14/90	343.77	343.72	343.73	343.79	343.78	343.79
12/05/90	343.74	343.72	343.73	343.67	343.79	343.79
12/22/91	343.73	343.71	343.71	343.78	343.77	343.77
02/05/91	343.70	343.69	343.69	343.79	343.75	343.75
03/14/91	343.69	343.68	343.61	343.76	343.78	343.69
04/04/91	343.74	343.70	343.70	343.75	343.75	343.75
04/09/91	343.73	343.70	343.69	343.78	343.75	343.74
04/16/91	343.70	343.70	343.71	343.75	343.78	343.74
04/24/91	343.74	343.74	343.70	343.75	343.76	343.75
05/08/91	343.76	343.73	343.74	343.81	343.77	343.78
05/14/91	343.76	343.75	343.75	343.79	343.79	343.79
05/21/91	343.80	343.79	343.78	343.87	343.85	343.83
05/29/91	343.84	343.84	343.84	343.88	343.87	343.88
06/08/91	343.88	343.88	343.88	343.96	343.92	343.97
06/14/91	343.91	343.91	343.91	343.97	343.97	343.97
06/19/91	343.92	343.93	343.90	344.03	344.01	343.97
06/26/91	343.90	343.90	343.91	343.99	343.98	343.98
07/10/91	344.01	343.96	343.97	344.09	344.09	344.06
07/18/91	344.00	344.00	344.00	344.13	344.12	344.12
07/24/91	343.95	343.90	343.95	344.09	344.09	344.09
08/01/91	343.93	343.92	343.91	344.05	344.06	344.10
08/20/91	343.83	343.83	343.83	343.98	343.97	343.98
08/29/91	343.81	343.81	343.81	343.95	343.95	343.95
09/03/91	343.80	343.80	343.80	343.94	343.94	343.94
09/13/91	343.80	343.80	343.80	343.92	343.92	343.92
09/24/91	343.83	343.83	343.83	343.95	343.95	343.95
10/10/91	343.91	343.90	343.87	343.95	343.95	343.91
10/22/91	343.92	343.91	343.89	343.99	343.98	343.99
11/15/91	343.93	343.93	343.94	344.02	344.01	344.02
11/21/91	343.95	343.95	343.95	344.04	344.03	344.03
12/17/91	344.07	344.00	343.99	344.13	344.07	344.07
01/21/92	344.00	343.99	343.99	344.07	344.07	344.07
01/30/92	343.99	343.99	343.99	344.06	344.06	344.06

APPENDIX IV

HYDRAULIC HEAD CALCULATIONS
-UNSATURATED ZONE-

Appendix IV

Determination of hydraulic heads in the unsaturated zone was done with tensiometers obtained from Soil Measurement Systems. The tensiometers consisted of 1.9 centimetre PVC pipe epoxied to a porous ceramic cup on the bottom and a clear glass tube on the top. A rubber septum was used to seal the glass tube. Tension or capillary pressure was obtained by inserting a needle attached to a pressure transducer into the septum.

Tensiometers were installed at the location of monitoring well nest EV-11 to 15, the same location as the neutron access tube. Holes were drilled for the tensiometers with a 1.9 centimetre diameter hand auger. The tensiometers were inserted into the holes and a slurry was poured around the tensiometer to provide a seal. The slurry consisted of tap water mixed with soil cuttings collected near the bottom of the hole.

Hydraulic Head Calculations - Unsaturated Zone

Procedures:

1) Field readings obtained are in mbars.
   (Note: 1 mbar = 1 cm of water at 25°C).

2) Convert field readings from mbar to cm.

3) Determine and correct for column of water in tensiometer.

4) Determine elevation head at midpoint of porous cup for each tensiometer.

5) Add corrected tension head (Y) to the elevation head (z) to get the hydraulic head (h). $h = Y + z$

Tensiometer readings (mbar)

DATE	DAY	2 FT LEVEL	4 FT LEVEL	6 FT LEVEL	8 FT LEVEL
05/17/91	253	-146	-175	-209	-253
05/30/91	266	-152	-174	-210	-266
06/08/91	275	-163	-182	-211	-261
06/18/91	285	-165	-188	-216	-266
07/09/91	306	-136	-162	-207	-263
07/23/91	320	-148	-174	-212	-265
08/20/91	347	-146	-177	-211	-262
09/25/91	383	-141	-179	-217	-270
10/11/91	399	-172	-184	-213	-270
10/23/91	411	-184	-189	-215	-268

Tensiometer readings (mbar converted to cm)

DATE	DAY	2 FT LEVEL	4 FT LEVEL	6 FT LEVEL	8 FT LEVEL
05/17/91	253	-146	-175	-209	-253
05/30/91	266	-152	-174	-210	-266
06/08/91	275	-163	-182	-211	-261
06/18/91	285	-165	-188	-216	-266
07/09/91	306	-136	-162	-207	-263
07/23/91	320	-148	-174	-212	-265
08/20/91	347	-146	-177	-211	-262
09/25/91	383	-141	-179	-217	-270
10/11/91	399	-172	-184	-213	-270
10/23/91	411	-184	-189	-215	-268

Column of water in tensiometer (cm)

2 FT LEVEL	4 FT LEVEL	6 FT LEVEL	8 FT LEVEL
66.5	127.5	187.5	248.5

Tension head corrected for water column (cm)

DATE	DAY	2 FT LEVEL	4 FT LEVEL	6 FT LEVEL	8 FT LEVEL
05/17/91	253	-79.5	-47.5	-21.5	-4.5
05/30/91	266	-85.5	-46.5	-22.5	-17.5
06/08/91	275	-96.5	-54.5	-23.5	-12.5
06/18/91	285	-98.5	-60.5	-28.5	-17.5
07/09/91	306	-69.5	-34.5	-19.5	-14.5
07/23/91	320	-81.5	-46.5	-24.5	-16.5
08/20/91	347	-79.5	-49.5	-23.5	-13.5
09/25/91	383	-74.5	-51.5	-29.5	-21.5
10/11/91	399	-105.5	-56.5	-25.5	-21.5
10/23/91	411	-117.5	-61.5	-27.5	-19.5

Elevation at midpoint of porous cup (metres)

2 FT LEVEL	4 FT LEVEL	6 FT LEVEL	8 FT LEVEL
347.98	347.37	346.69	346.16

Hydraulic head (metres)

DATE	DAY	2 FT LEVEL	4 FT LEVEL	6 FT LEVEL	8 FT LEVEL
05/17/91	253	347.185	346.895	346.475	346.115
05/30/91	266	347.125	346.905	346.465	345.985
06/08/91	275	347.015	346.825	346.455	346.035
06/18/91	285	346.995	346.765	346.405	345.985
07/09/91	306	347.285	347.025	346.495	346.015
07/23/91	320	347.165	346.905	346.445	345.995
08/20/91	347	347.185	346.875	346.455	346.025
09/25/91	383	347.235	346.855	346.395	345.945
10/11/91	399	346.925	346.805	346.435	345.945
10/23/91	411	346.805	346.755	346.415	345.965

APPENDIX V

NEUTRON PROBE MOISTURE DETERMINATIONS

Appendix V

A neutron access tube consisting of a 5-centimetre I.D. by 3-metre length aluminum conduit pipe was placed in the vicinity of well EV-13. The bottom of the access tube was plugged with an adjustable drain plug to keep water out of the tube. The hole for the access tube was drilled with a 5-centimeter O.D. hand auger.

Sediment samples were collected with a hand auger to determine bulk density and moisture content. The hand auger was constructed with an internal sleeve which allowed collection of a uniform sample volume. Samples were collected at 15-centimetre intervals and placed in air-tight sample containers.

The sediment samples were weighed, oven dried, and weighed again. The bulk density and moisture content on a dry weight basis were calculated and the volumetric water content was determined.

Neutron probe readings were obtained with a Campbell Pacific Nuclear Model 503 hydroprobe at 15-centimetre intervals within the access tube. Measurements were made as the hydroprobe was lowered and raised within the access tube and averaged for each depth interval. Standard counts were made with the hydroprobe before and after measurements within the access tube. An average of the standard counts was calculated and the ratio of hydroprobe readings within the access tube to the average standard counts was made.

A regression equation was derived to convert neutron count readings to soil moisture content (soil moisture content = -1.7054 + 16.4170n; where n = volumetric soil water content). Because of problems encountered in the installation of the access tube, only the top 1.83 metres of the access tube was used for soil moisture content determinations.

Neutron Probe Data Versus Moisture Content

Results of Regression Analysis:

Constant	-1.70541
Std. Err. of Y Est.	1.118964
R Squared	0.902795
No. of Observations	9
Degrees of Freedom	7
x coefficient	16.41704
Std. Err. of Coef.	2.036088

Moisture Content(%)	NP counts/ STD counts
23.20	1.44
23.19	1.56
22.88	1.50
20.61	1.46
21.54	1.36
21.98	1.35
18.74	1.29
15.24	1.06
14.44	0.99

$w = -1.70541 + (16.41704 \times n)$

where:

w = Moisture content (percent)
n = Ratio (Neutron probe counts/standard counts)

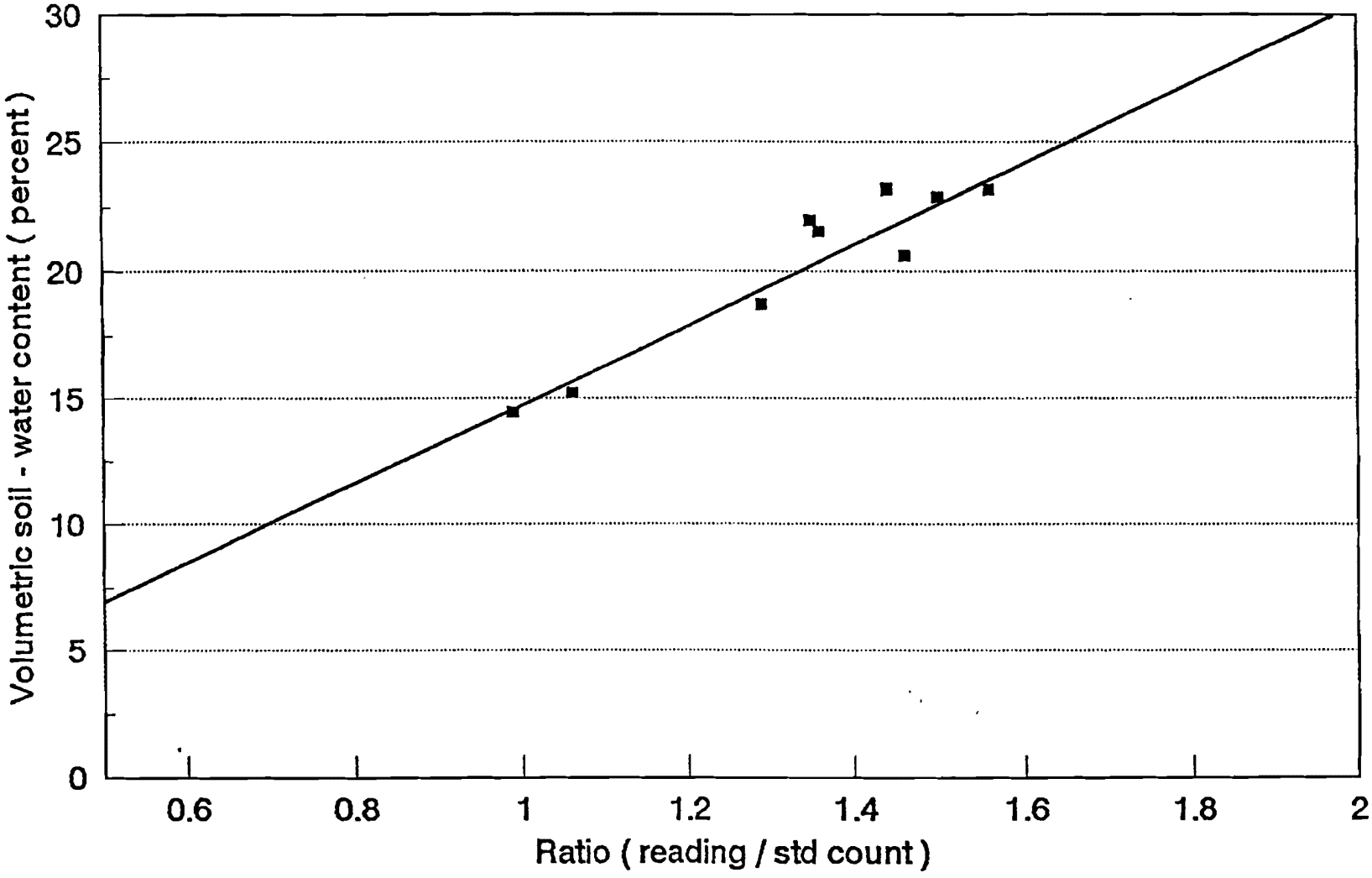


Figure 14. Field calibration curve for neutron probe (upper 1.5 metres of soil column).

NEUTRON PROBE COUNTS

DATE	05/02/91	05/17/91	05/30/91	06/08/91	06/19/91
DEPTH (metres)					
0.30	35904	34928	35513	35573	36226
0.46	40895	39321	39685	37885	38687
0.61	39666	38169	38667	37933	38335
0.76	37060	36677	37078	35477	35330
0.91	36298	35411	35403	35416	35180
1.07	35669	35238	35274	34701	34399
1.22	34220	33658	33324	33125	32867
1.37	30145	27304	27415	26666	26528
1.52	25732	25960	25767	25354	24873
1.68	22422	25488	25451	24896	24690
1.83	25302	28660	28239	27720	27017
1.98	26228	30175	30148	30108	29023
2.13	23708	30805	29182	29078	28203
2.29	20510	26579	25370	25370	24475
2.44	20868	26498	25545	25462	24947
2.59	19794	24688	24168	24049	23399
2.74	19148	22369	23535	23691	22995
2.90	20164	22467	24799	24810	24341

NEUTRON PROBE COUNTS (standard)

DATE	05/02/91	05/17/91	05/30/91	06/08/91	06/19/91
	25943	25803	25797	25783	26130

RATIO (neutron probe counts/standard counts)

DATE	05/02/91	05/17/91	05/30/91	06/08/91	06/19/91
DEPTH (metres)					
0.30	1.38	1.35	1.38	1.38	1.39
0.46	1.58	1.52	1.54	1.47	1.48
0.61	1.53	1.48	1.50	1.47	1.47
0.76	1.43	1.42	1.44	1.38	1.35
0.91	1.40	1.37	1.37	1.37	1.35
1.07	1.37	1.37	1.37	1.35	1.32
1.22	1.32	1.30	1.29	1.28	1.26
1.37	1.16	1.06	1.06	1.03	1.02
1.52	0.99	1.01	1.00	0.98	0.95
1.68	0.86	0.99	0.99	0.97	0.94
1.83	0.98	1.11	1.09	1.08	1.03
1.98	1.01	1.17	1.17	1.17	1.11
2.13	0.91	1.19	1.13	1.13	1.08
2.29	0.79	1.03	0.98	0.98	0.94
2.44	0.80	1.03	0.99	0.99	0.95
2.59	0.76	0.96	0.94	0.93	0.90
2.74	0.74	0.87	0.91	0.92	0.88
2.90	0.78	0.87	0.96	0.96	0.93

MOISTURE CONTENT (percent)

DEPTH (metres)	DATE 05/02/91	05/17/91	05/30/91	06/08/91	06/19/91
0.30	21.0	20.5	20.9	21.0	21.1
0.46	24.2	23.3	23.6	22.4	22.6
0.61	23.4	22.6	22.9	22.5	22.4
0.76	21.8	21.6	21.9	20.9	20.5
0.91	21.3	20.8	20.8	20.9	20.4
1.07	20.9	20.7	20.7	20.4	19.9
1.22	20.0	19.7	19.5	19.4	18.9
1.37	17.4	15.7	15.7	15.3	15.0
1.52	14.6	14.8	14.7	14.4	13.9
1.68	12.5	14.5	14.5	14.2	13.8
1.83	14.3	16.5	16.3	15.9	15.3

NEUTRON PROBE COUNTS

DATE	07/10/91	07/23/91	08/20/91	09/25/91	10/11/91
DEPTH (metres)					
0.30	37081	37490	37648	37357	36572
0.46	38804	39408	39033	39422	39428
0.61	38686	38516	38467	38838	38176
0.76	36668	36716	36558	35858	37258
0.91	35620	35640	35430	35153	34871
1.07	35140	34977	34942	35109	34770
1.22	33715	33616	33021	33584	33007
1.37	27291	27454	27093	26470	26711
1.52	26050	26020	25521	25289	25469
1.68	25457	25326	24531	24214	24684
1.83	28025	27749	27798	27011	27332
1.98	29604	29435	29751	28977	28935
2.13	28380	28945	28438	27404	27984
2.29	24817	24952	24945	23757	26166
2.44	24968	25190	25093	23847	24472
2.59	23637	24396	23802	22952	23991
2.74	23157	23136	22726	21996	22475
2.90	24729	24389	24006	23149	23675

NEUTRON PROBE COUNTS (standard)

DATE	07/10/91	07/23/91	08/20/91	09/25/91	10/11/91
	25588	25866	25845	25871	26017

RATIO (neutron probe counts/standard counts)

DATE	07/10/91	07/23/91	08/20/91	09/25/91	10/11/91
DEPTH (metres)					
0.30	1.45	1.45	1.46	1.44	1.41
0.46	1.52	1.52	1.51	1.52	1.52
0.61	1.51	1.49	1.49	1.50	1.47
0.76	1.43	1.42	1.41	1.39	1.43
0.91	1.39	1.38	1.37	1.36	1.34
1.07	1.37	1.35	1.35	1.36	1.34
1.22	1.32	1.30	1.28	1.30	1.27
1.37	1.07	1.06	1.05	1.02	1.03
1.52	1.02	1.01	0.99	0.98	0.98
1.68	0.99	0.98	0.95	0.94	0.95
1.83	1.10	1.07	1.08	1.04	1.05
1.98	1.16	1.14	1.15	1.12	1.11
2.13	1.11	1.12	1.10	1.06	1.08
2.29	0.97	0.96	0.97	0.92	1.01
2.44	0.98	0.97	0.97	0.92	0.94
2.59	0.92	0.94	0.92	0.89	0.92
2.74	0.90	0.89	0.88	0.85	0.86
2.90	0.97	0.94	0.93	0.89	0.91

MOISTURE CONTENT (percent)

DEPTH (metres)	DATE 07/10/91	07/23/91	08/20/91	09/25/91	10/11/91
0.30	22.1	22.1	22.2	22.0	21.4
0.46	23.2	23.3	23.1	23.3	23.2
0.61	23.1	22.7	22.7	22.9	22.4
0.76	21.8	21.6	21.5	21.1	21.8
0.91	21.2	20.9	20.8	20.6	20.3
1.07	20.8	20.5	20.5	20.6	20.2
1.22	19.9	19.6	19.3	19.6	19.1
1.37	15.8	15.7	15.5	15.1	15.2
1.52	15.0	14.8	14.5	14.3	14.4
1.68	14.6	14.4	13.9	13.7	13.9
1.83	16.3	15.9	16.0	15.4	15.5

NEUTRON PROBE COUNTS

DEPTH (metres)	DATE 10/22/91
0.30	37280
0.46	39238
0.61	38126
0.76	37202
0.91	34772
1.07	34511
1.22	32400
1.37	27076
1.52	24846
1.68	23867
1.83	26719
1.98	28259
2.13	27581
2.29	24031
2.44	24147
2.59	23526
2.74	22178
2.90	23373

NEUTRON PROBE COUNTS (standard)

DATE 10/22/91
25826

RATIO (neutron probe counts/standard counts)

DEPTH (metres)	DATE 10/22/91
0.30	1.44
0.46	1.52
0.61	1.48
0.76	1.44
0.91	1.35
1.07	1.34
1.22	1.25
1.37	1.05
1.52	0.96
1.68	0.92
1.83	1.03
1.98	1.09
2.13	1.07
2.29	0.93
2.44	0.93
2.59	0.91
2.74	0.86
2.90	0.91

MOISTURE CONTENT (percent)

DEPTH (metres)	DATE 10/22/91
0.30	22.0
0.46	23.2
0.61	22.5
0.76	21.9
0.91	20.4
1.07	20.2
1.22	18.9
1.37	15.5
1.52	14.1
1.68	13.5
1.83	15.3

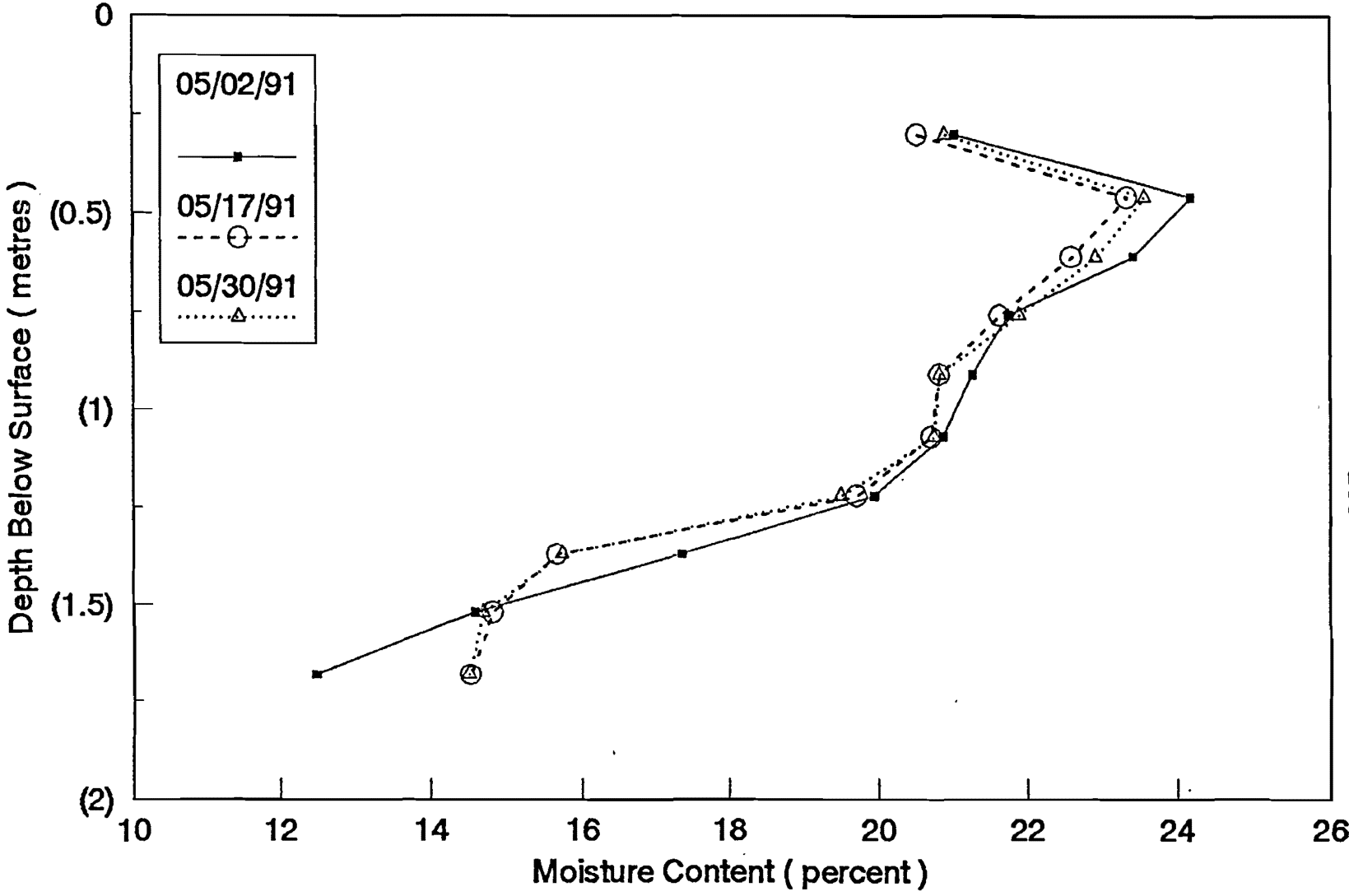


Figure 15. Moisture content versus depth profile (May 1991).

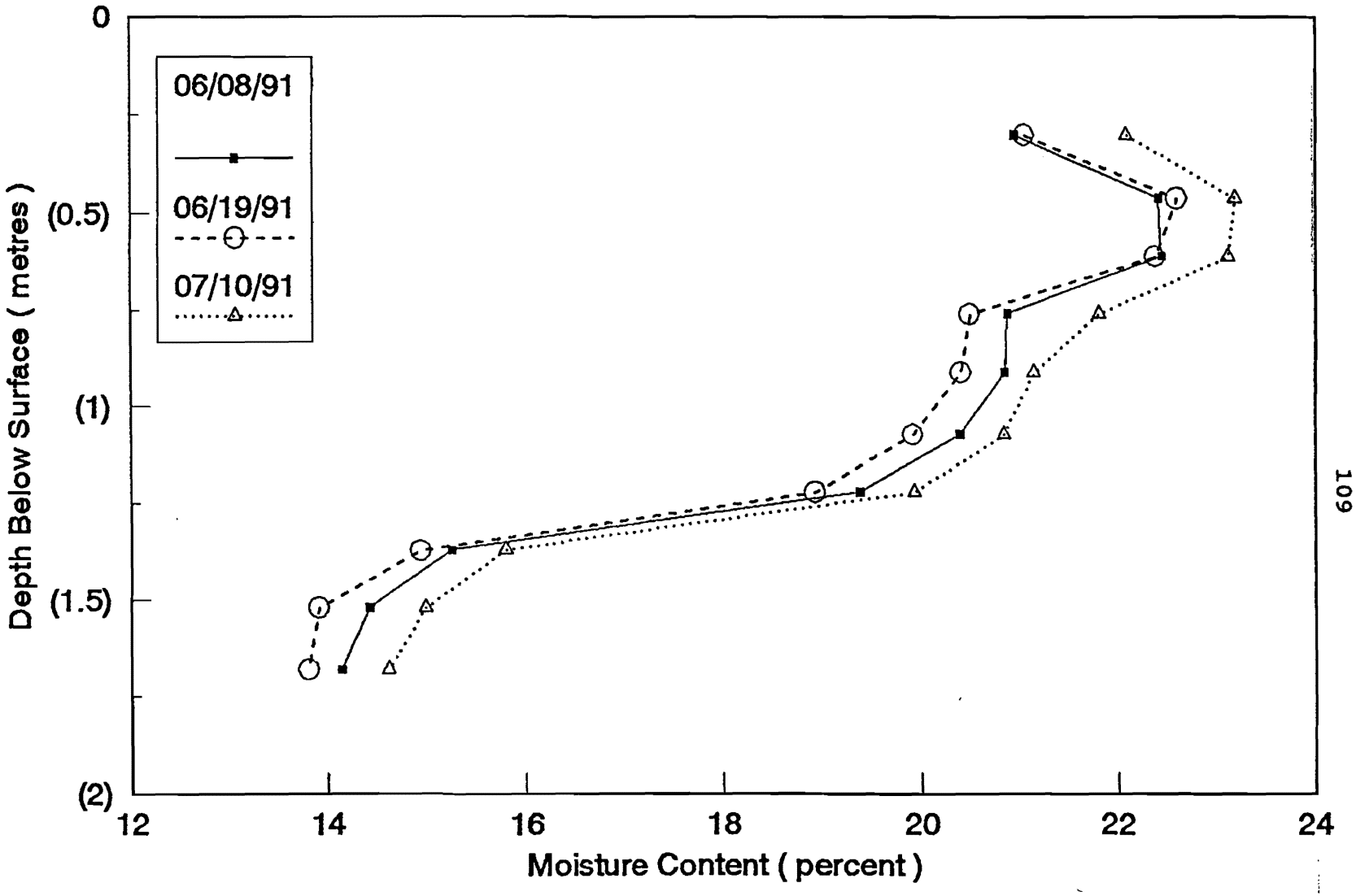


Figure 16. Moisture content versus depth profile (June and July 1991).

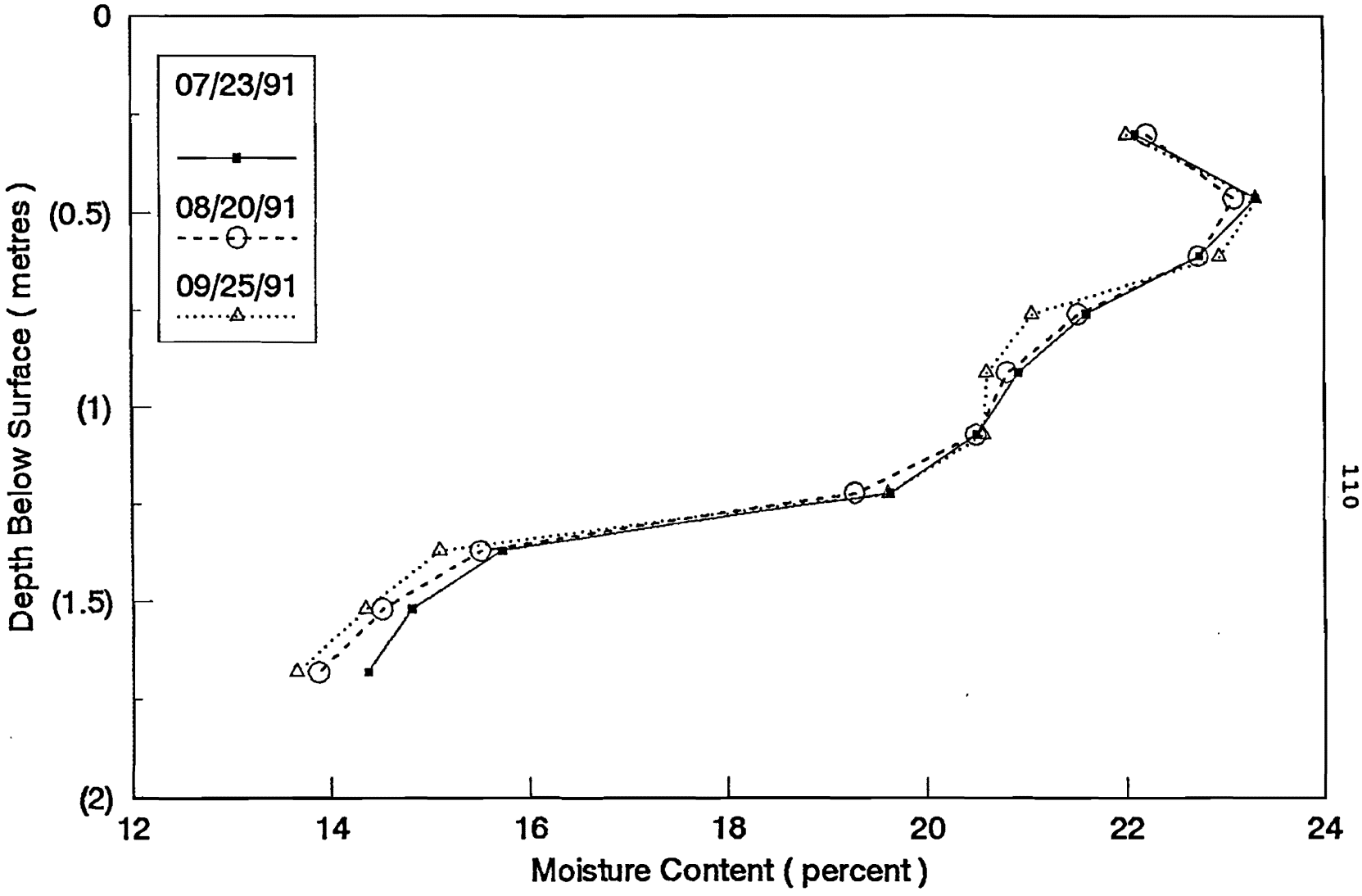


Figure 17. Moisture content versus depth profile (July, August, and September 1991).

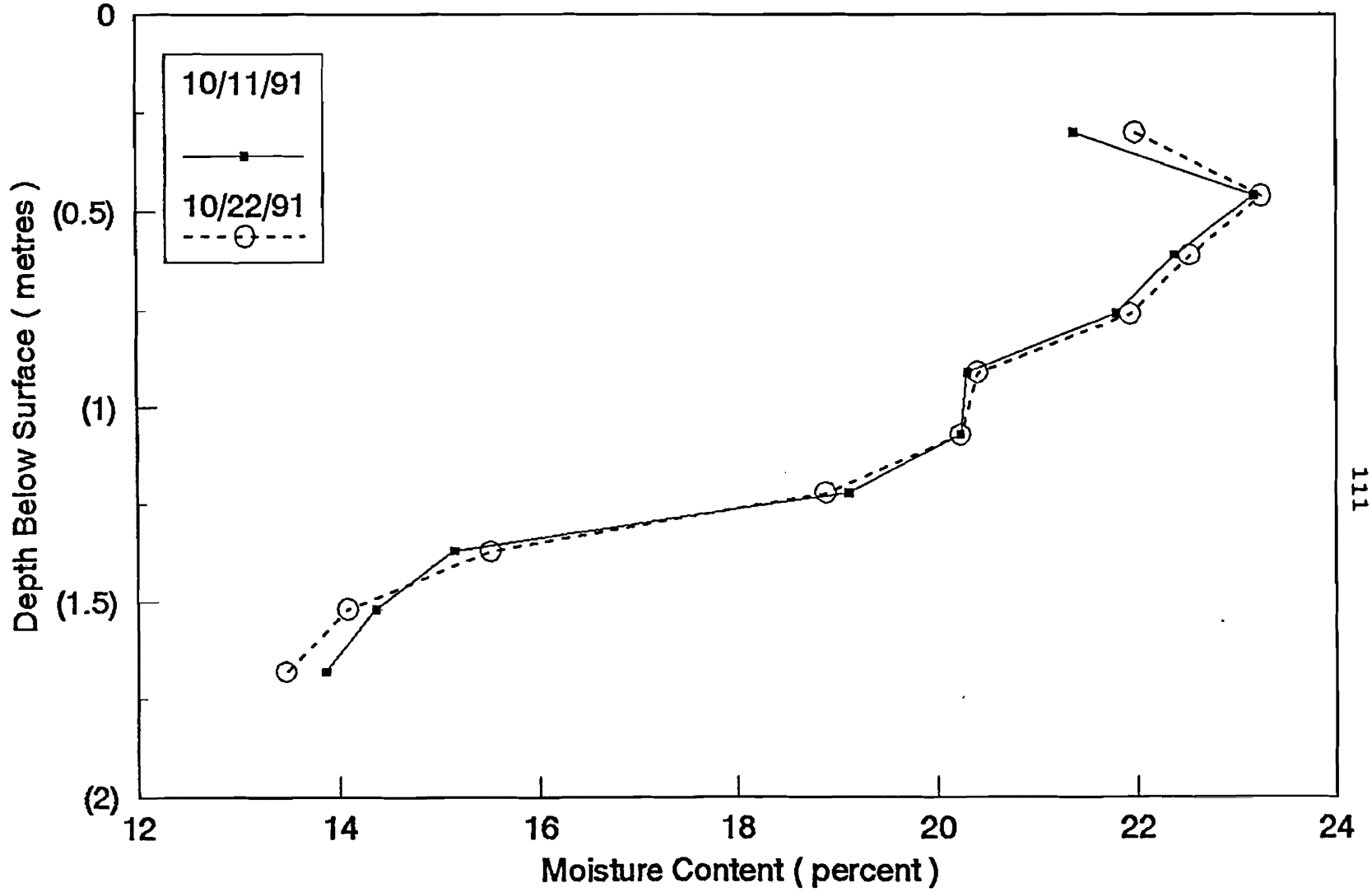


Figure 18. Moisture content versus depth profile (October 1991).

APPENDIX VI

HYDRAULIC CONDUCTIVITY (K) CALCULATIONS

Appendix VI

Hydraulic conductivity in the saturated zone was estimated by slug tests on wells EV-12, EV-14, and EV-15 (January 30, 1992) by the method of Bouwer (1989). This method estimates the hydraulic conductivity of the aquifer around the screen of the well for fully or partially penetrating wells in unconfined aquifers. Wells were pressurized with nitrogen gas to depress the water levels. The pressure was released through the use of a ball valve and the rate of recovery was measured with a pressure transducer and Terra Systems Incorporated data logger.

Calculation of ln (R_e/l_w): (from Bouwer, 1989)

$$\text{where } \ln\left[\frac{R_e}{r_w}\right] = \left[\frac{1.1}{\ln(L_w/r_w)} + \frac{A+B\ln(H-L_w/r_w)}{L_e/r_w}\right]$$

and:

r_w = radial distance between well center and undisturbed portion of aquifer (metres)
H = thickness of saturated portion of aquifer (metres)
L_e = length of screened section of well (metres)
L_w = distance between water table and bottom of well (metres)
A,B = dimensionless parameters as a function of l_e/r_s for ln (R_e/r_w) calculations (from Bouwer, 1989)
R_e = effective radial distance over which y is dissipated (metres).
y = vertical difference between water level in well and static water table (metres)

Data for Calculation of ln (R_e/r_w):

Parameter	EV-12	EV-14	EV-15
r_w	0.10	0.10	0.10
H	18.28	18.28	18.28
L_e	0.75	0.75	0.75
L_w	13.91	7.69	4.67
A	1.75	1.75	1.75
B	0.25	0.25	0.25
L_e/r_w	7.25	7.25	7.25

Calculated $\ln\left(\frac{R_e}{r_w}\right)$:

Well	EV-12	EV-14	EV-15
	1.72	1.56	1.46

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2L_e} \frac{1}{t_2 - t_1} \ln\left(\frac{y_1}{y_2}\right)$$

r_c = radius of casing (0.027 metres)
y_1 = y at time 1 (metres)
y_2 = y at time 2 (metres)
t = time (seconds)
K = hydraulic conductivity (metres per second)

Hydraulic Conductivity Results for Well EV-12

Slug Test EV-12-1

where: t_1 = 14 seconds
t_2 = 70 seconds
y_1 = 4.73 metres
y_2 = 0.09 metres

$$K = \frac{(0.027)^2\ (1.72)}{2\ (0.75)} \left(\frac{1}{70-14}\right) \ln \frac{4.73}{0.09}$$

$K = 5.9 \times 10^{-5}$ metres/second

Slug Test EV-12-2

where: t_1 = 14 seconds
t_2 = 68 seconds
y_1 = 4.78 metres
y_2 = 0.13 metres

$K = 5.6 \times 10^{-5}$ metres/second

Slug Test EV-12-3

where: t_1 = 26 seconds
t_2 = 80 seconds
y_1 = 2.22 metres
y_2 = 0.06 metres

$K = 5.6 \times 10^{-5}$ metres/second

Hydraulic Conductivity Results for Well EV-14

Slug Test EV-14-1

where: t_1 = 2 seconds
t_2 = 8 seconds
y_1 = 1.12 metres
y_2 = 0.03 metres

$K = 4.6 \times 10^{-4}$ metres/second

Slug Test EV-14-2

where: t_1 = 2 seconds
t_2 = 10 seconds
y_1 = 1.73 metres
y_2 = 0.02 metres

$K = 4.2 \times 10^{-4}$ metres/second

Slug Test EV-14-3

where: t_1 = 2 seconds
t_2 = 10 seconds
y_1 = 1.85 metres
y_2 = 0.02 metres

$K = 4.3 \times 10^{-4}$ metres/second

Hydraulic Conductivity Results for Well EV-15

Slug Test EV-15-1

where: t_1 = 4 seconds
t_2 = 10 seconds
y_1 = 0.46 metres
y_2 = 0.04 metres

$K = 2.9 \times 10^{-4}$ metres/second

Slug Test EV-15-2

where: t_1 = 2 seconds
t_2 = 10 seconds
y_1 = 0.99 metres
y_2 = 0.04 metres

$K = 2.8 \times 10^{-4}$ metres/second

Elk Valley Slug Test EV-12-1

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	2.11	11.58
2	3.43	10.27
4	4.72	8.97
6	5.76	7.93
8	6.71	6.98
10	7.55	6.15
12	8.30	5.39
14	8.96	4.73
16	9.57	4.13
18	10.10	3.60
20	10.51	3.18
22	10.93	2.77
24	11.29	2.41
26	11.60	2.09
28	11.89	1.81
30	12.10	1.59
32	12.33	1.37
34	12.51	1.19
36	12.67	1.03
38	12.81	0.89
40	12.93	0.77
42	13.03	0.67
44	13.12	0.57
46	13.20	0.49
48	13.26	0.44
50	13.32	0.37
52	13.37	0.33
54	13.41	0.28
56	13.45	0.24
58	13.49	0.21
60	13.52	0.18
62	13.54	0.16
64	13.56	0.14
66	13.58	0.12
68	13.59	0.10
70	13.60	0.09
72	13.62	0.08
74	13.63	0.07
76	13.63	0.06
78	13.64	0.05
80	13.65	0.05

Elk Valley Slug Test EV-12-2

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	2.70	11.00
2	3.89	9.80
4	4.97	8.73
6	5.92	7.77
8	6.80	6.89
10	7.59	6.10
12	8.30	5.40
14	8.92	4.78
16	9.49	4.20
18	10.00	3.69
20	10.46	3.24
22	10.85	2.84
24	11.20	2.49
26	11.48	2.22
28	11.76	1.94
30	12.01	1.69
32	12.22	1.47
34	12.39	1.30
36	12.56	1.13
38	12.71	0.98
40	12.83	0.87
42	12.94	0.75
44	13.04	0.65
46	13.12	0.58
48	13.19	0.51
50	13.26	0.44
52	13.31	0.39
54	13.36	0.34
56	13.40	0.29
58	13.44	0.26
60	13.47	0.22
62	13.50	0.20
64	13.53	0.17
66	13.55	0.15
68	13.56	0.13
70	13.58	0.11
72	13.59	0.10
74	13.61	0.09
76	13.62	0.08
78	13.63	0.07
80	13.63	0.06
82	13.64	0.06
84	13.65	0.05

Elk Valley Slug Test EV-12-3

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	1.59	12.10
2	2.78	10.91
4	3.99	9.70
6	4.97	8.72
8	5.85	7.84
10	6.68	7.01
12	7.42	6.27
14	8.09	5.60
16	8.69	5.00
18	9.25	4.44
20	9.75	3.94
22	10.19	3.50
24	10.55	3.14
26	10.91	2.78
28	11.23	2.46
30	11.52	2.17
32	11.77	1.92
34	11.98	1.71
36	12.18	1.51
38	12.36	1.33
40	12.51	1.18
42	12.65	1.04
44	12.78	0.91
46	12.88	0.81
48	12.98	0.71
50	13.07	0.62
52	13.14	0.55
54	13.21	0.48
56	13.27	0.42
58	13.31	0.38
60	13.36	0.33
62	13.40	0.29
64	13.43	0.26
66	13.47	0.22
68	13.49	0.20
70	13.52	0.17
72	13.54	0.15
74	13.56	0.13
76	13.57	0.12
78	13.59	0.10
80	13.60	0.09
82	13.61	0.08
84	13.62	0.07
86	13.63	0.06
88	13.63	0.06
90	13.64	0.05

Elk Valley Slug Test EV-14-1

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	3.80	2.86
2	5.55	1.12
4	6.30	0.36
6	6.57	0.10
8	6.64	0.03
10	6.66	0.01
12	6.66	0.00
14	6.66	0.00
16	6.66	0.00
18	6.66	0.00
20	6.66	0.00

Elk Valley Slug Test EV-14-2

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	2.15	4.52
2	4.94	1.73
4	6.04	0.63
6	6.48	0.19
8	6.62	0.05
10	6.65	0.02
12	6.66	0.01
14	6.67	0.00
16	6.67	0.00
18	6.67	0.00
20	6.67	0.00

Elk Valley Slug Test EV-14-3

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	2.22	4.45
2	4.82	1.85
4	6.05	0.62
6	6.47	0.20
8	6.61	0.06
10	6.65	0.02
12	6.67	0.00
14	6.66	0.01
16	6.66	0.01
18	6.66	0.01
20	6.67	0.00

Elk Valley Slug Test EV-15-1

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	2.53	2.15
2	3.69	0.98
4	4.21	0.46
6	4.47	0.21
8	4.58	0.09
10	4.64	0.04
12	4.66	0.02
14	4.67	0.01
16	4.67	0.01
18	4.68	0.00
20	4.68	0.00

Elk Valley Slug Test EV-15-2

Elapsed Time(seconds)	Water Level (metres)	Drawdown - H (metres)
0	2.66	2.02
2	3.68	0.99
4	4.24	0.43
6	4.48	0.20
8	4.59	0.09
10	4.64	0.04
12	4.66	0.02
14	4.67	0.01
16	4.68	0.00
18	4.68	0.00
20	4.68	0.00

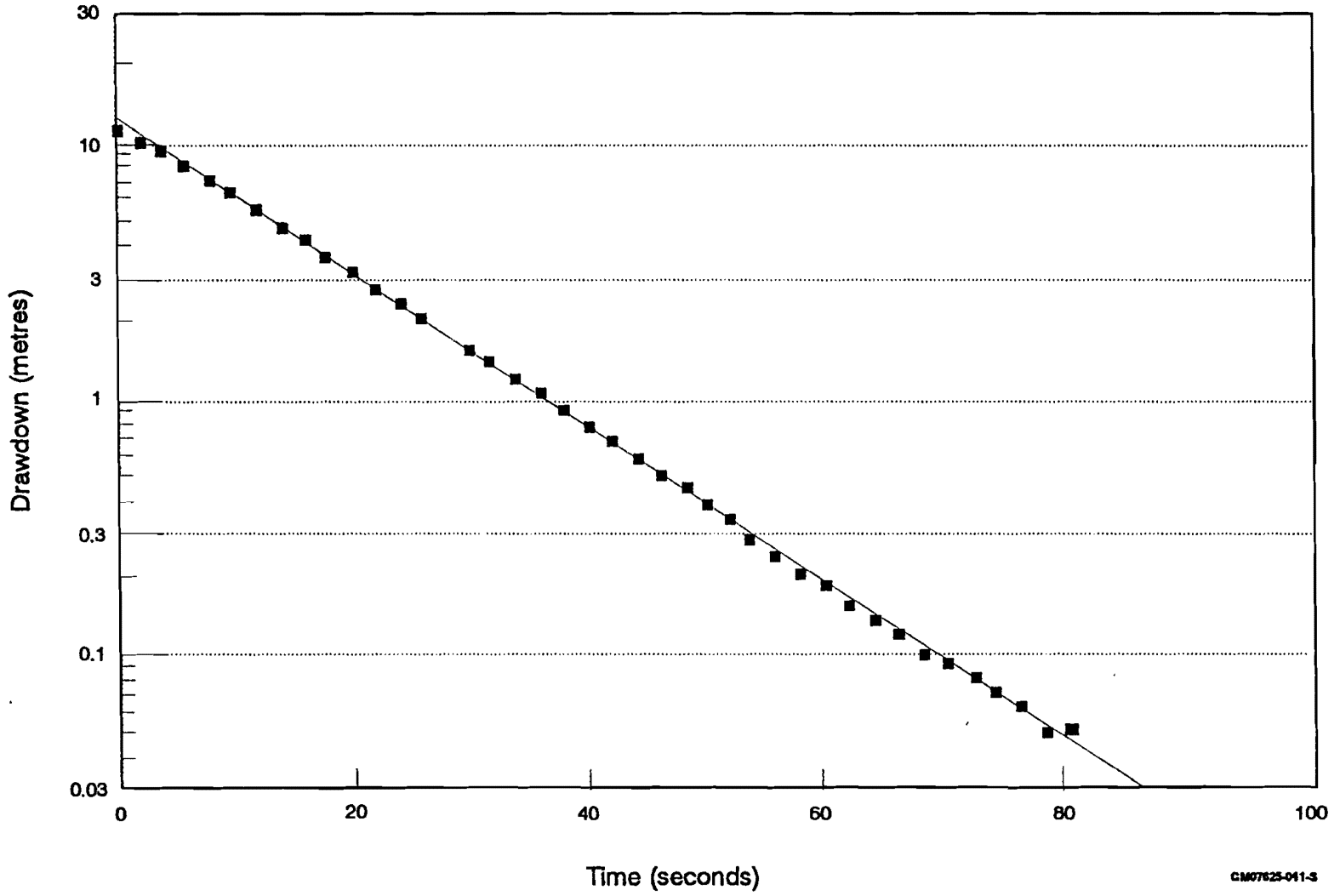


Figure 19. Slug test - drawdown versus time (EV-12-1).

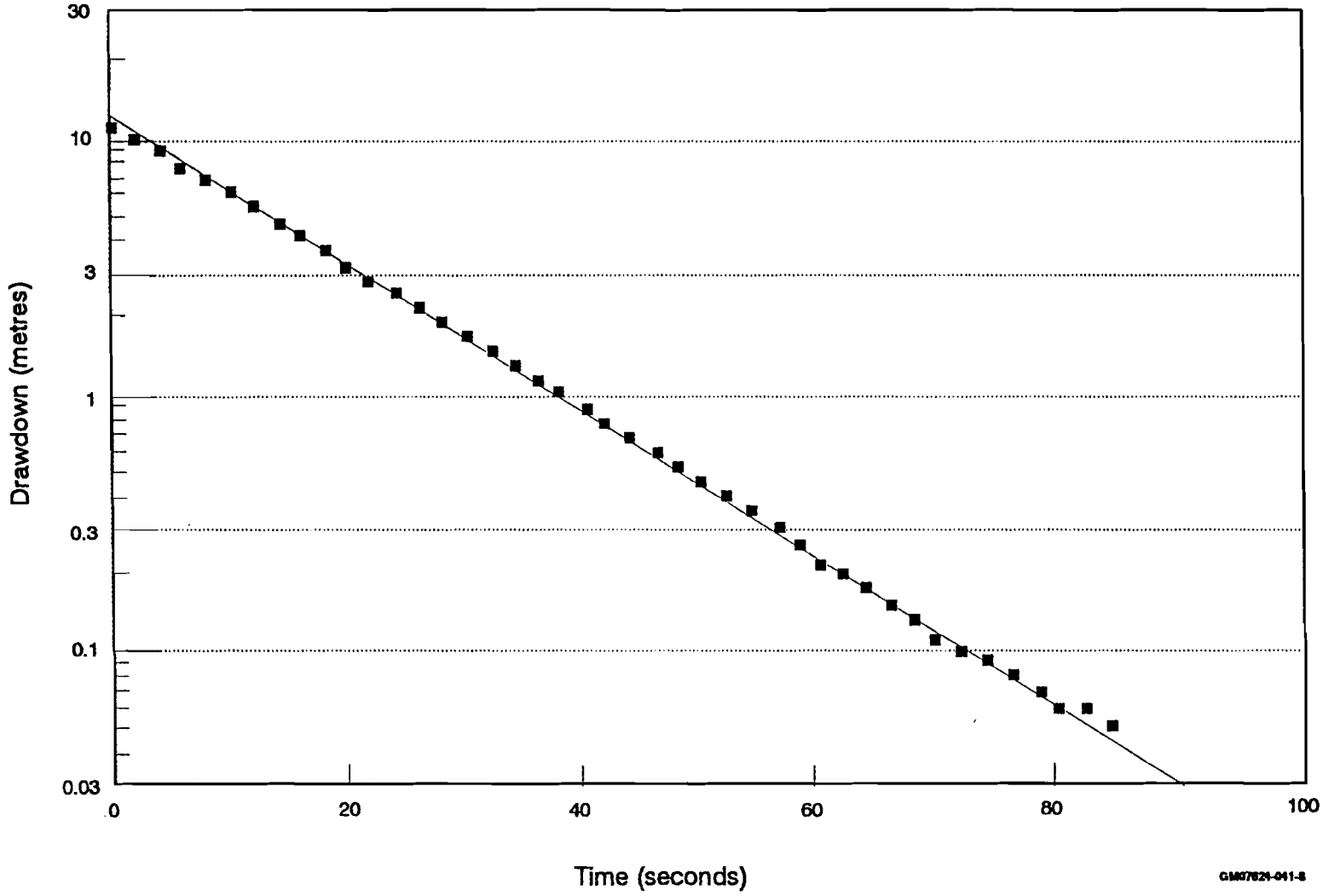


Figure 20. Slug test - drawdown versus time (EV-12-2).

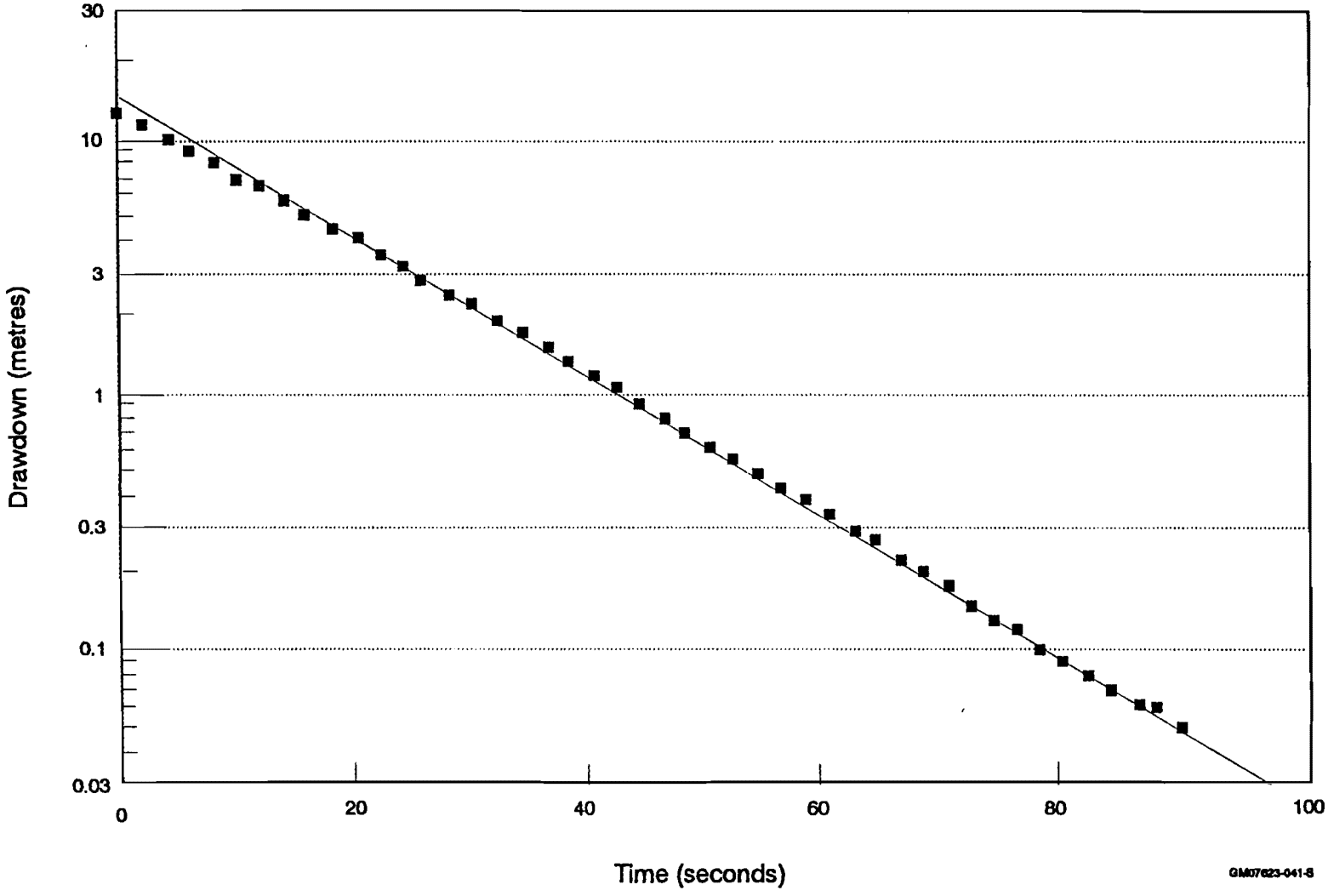


Figure 21. Slug test - drawdown versus time (EV-12-3).

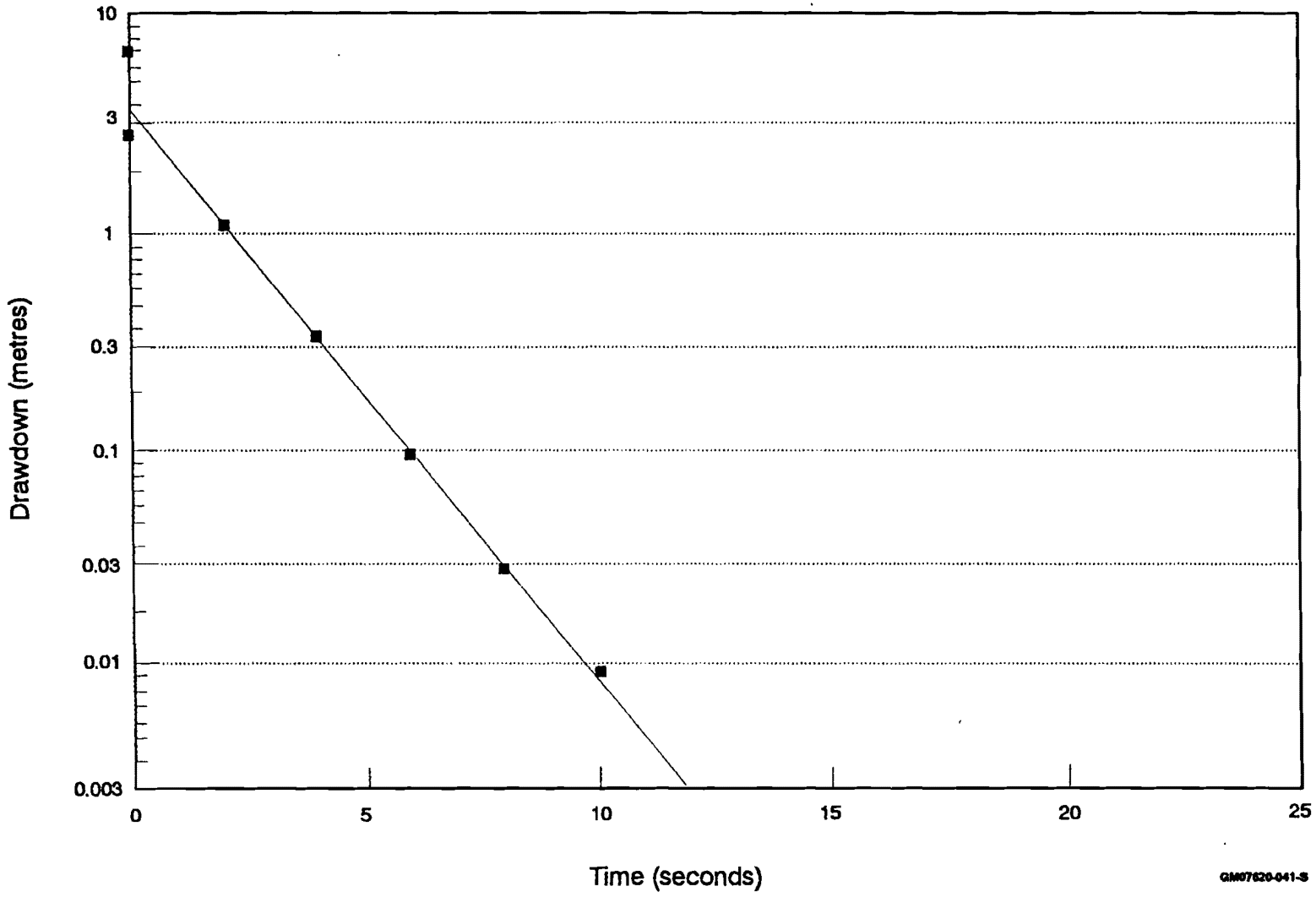


Figure 22. Slug test - drawdown versus time (EV-14-1).

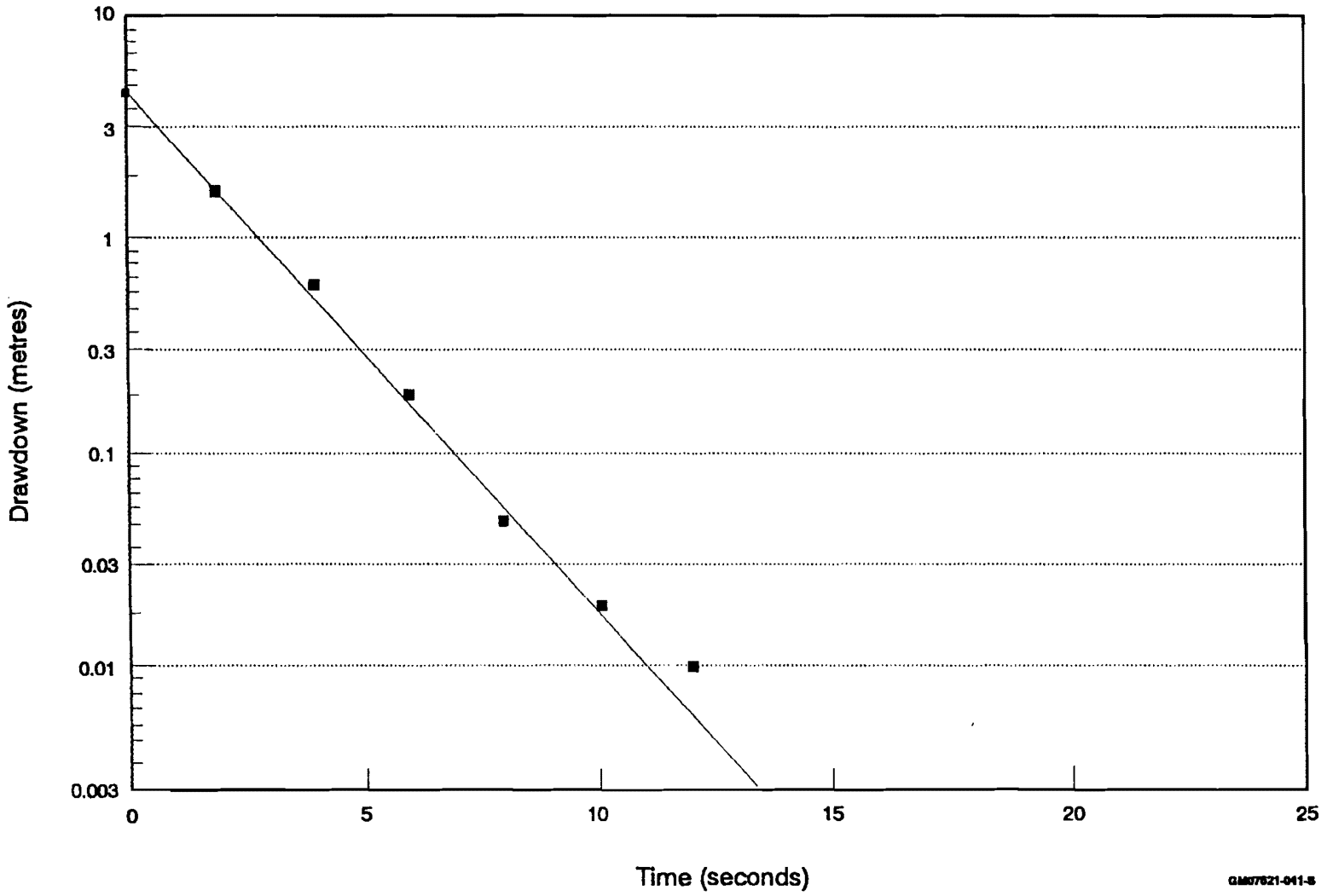


Figure 23. Slug test - drawdown versus time (EV-14-2).

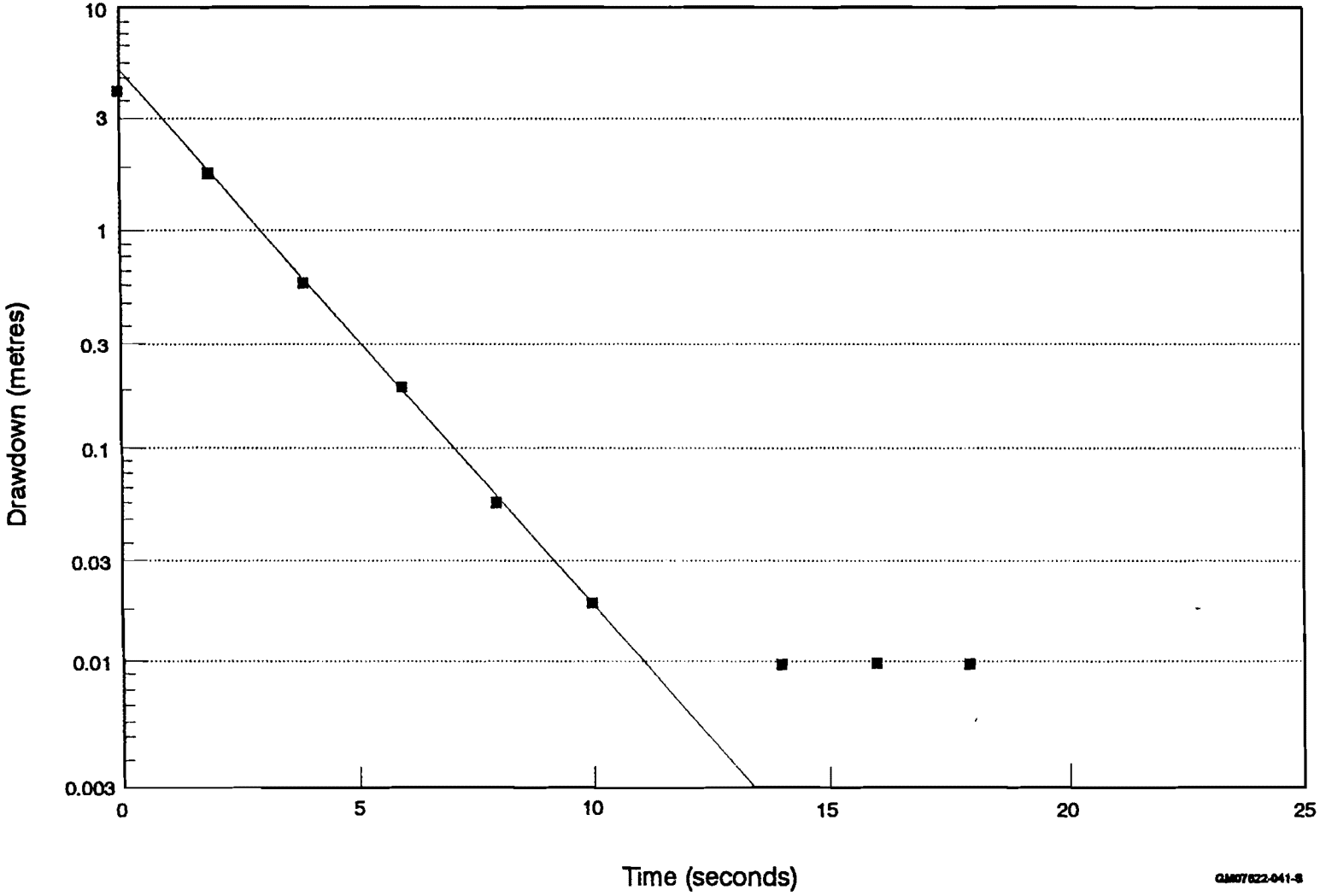


Figure 24. Slug test - drawdown versus time (EV-14-3).

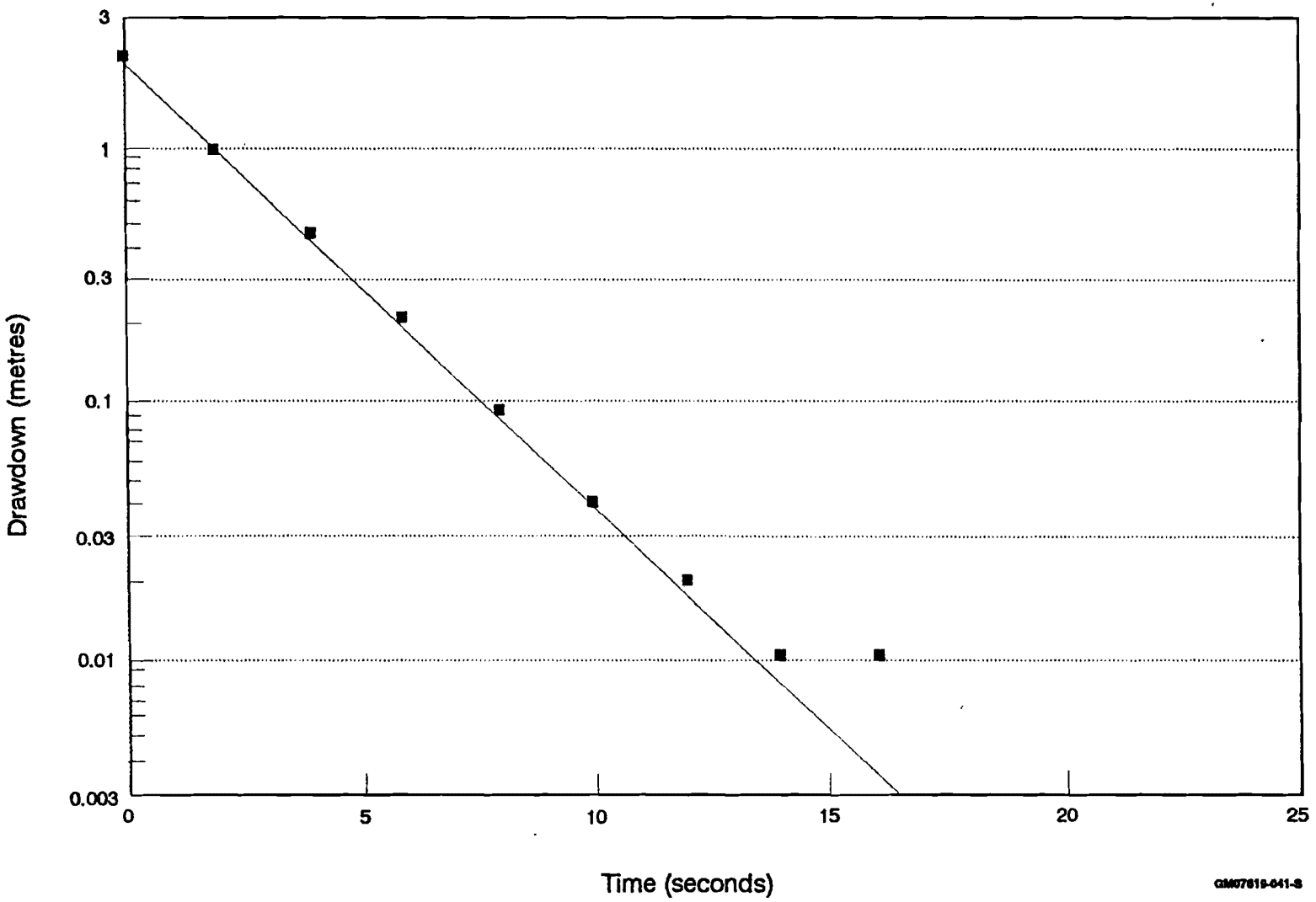


Figure 25. Slug test - drawdown versus time (EV-15-1).

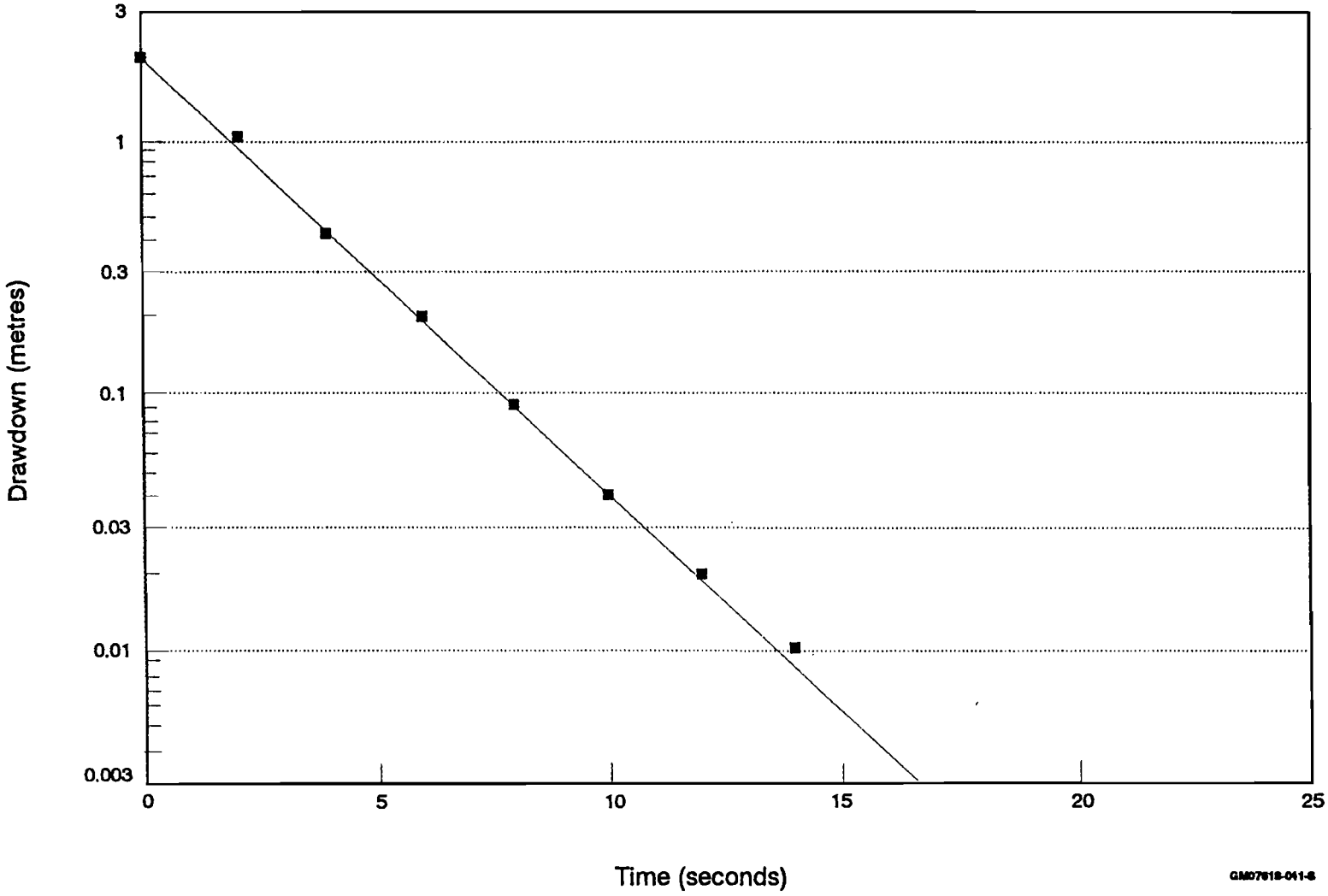


Figure 26. Slug test - drawdown versus time (EV-15-2).

APPENDIX VII

WATER QUALITY DATA

Appendix VII

Samples from the monitoring wells were collected with 316-stainless steel bailers. Decontamination procedures included distilled-deionized water, methanol, acetone, and then distilled-deionized water rinses of all sampling equipment. A minimum of three casing volumes of water were removed from the monitoring wells before final sample collection. Samples were collected after each casing volume removal and checked for conductivity, pH, and temperature. To insure that final samples were representative of insitu groundwater, conductivity and pH measurements on consecutive samples were required to be within 10 percent.

Laboratory analyses were conducted according to standard EPA and APHA procedures (Appendix X). Dissolved-oxygen and redox potential were measured in the field. Dissolved oxygen was measured within the well using a YSI 5739 dissolved-oxygen probe and a YSI model 58 dissolved-oxygen meter. Redox potential was determined on water pumped from the monitoring well into a flow-through cell to avoid exposure of the water to oxygen. Measurements were made with a Beckman 39273 platinum electrode and a Beckman PHI 12 Ph/ISE meter.

ABBREVIATIONS

TDS = Total Dissolved Solids
Cond. = Conductivity
Ca = Calcium
Mg = Magnesium
Na = Sodium
K = Potassium
Fe = Iron
Mn = Manganese
Cl = Chloride
F = Fluoride
HCO_3 = Bicarbonate
CO_3 = Carbonate
SO_4 = Sulfate
PO_4 = Phosphate
NO_3-N = Nitrate-nitrogen
TOC = Total Organic Carbon
TIC = Total Inorganic Carbon
TC = Total Carbon
ALK = Alkalinity
SAR = Sodium Absorption Ratio
Diss. = Dissolved
Oxy. = Oxygen
Calc. = Calculated
Lab = Laboratory

WATER QUALITY DATA FOR OCTOBER 1 AND 2, 1990

WELL I.D.	EV1-01	EV3-01	EV8-01	EV10-01
SAMPLE DATE	10/01/90	10/01/90	10/02/90	10/01/90
WATER QUALITY PARAMETER				
Temperature(°C)	11	8	10	10
Lab pH	7.56	7.30	7.48	7.42
Lab TDS(mg/L)	460	560	540	540
Lab Cond.(mS)	0.44	0.69	0.51	0.52
Ca(mg/L)	62	70	73	69
Mg(mg/L)	22	38	28	30
Na(mg/L)	2.1	32.0	4.1	3.9
K(mg/L)	2.1	6.5	2.3	1.8
Fe(mg/L)	<.02	0.084	<.02	<.02
Mn(mg/L)	0.039	1.200	<.01	<.01
Nitrate(NO_3-N, mg/L)	8.0	2.0	11.4	11.6
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.116	0.138	0.091	0.057
HCO_3 ALK(mg/L)	215	338	253	243
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	176	277	207	199
SO_4(mg/L)	33	88	28	36
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	1.1	10.0	4.2	1.9
F(mg/L)	<1	<1	<1	<1
TOC(mg/L) - FILTERED	53.5	91.4	28.1	32.6
% Sodium	0.00	0.00	0.00	0.00
Calc. $CaCO_3$ ALK(mg/L)	180	283	212	203
Calc. TDS(mg/L)	372	591	443	437
Calc. SAR	0.06	0.77	0.10	0.10
Calc. Hardness(mg/L)	275	331	298	296
Calc. Ion Balance(%)	-2.47	-2.43	-4.48	-4.43

WATER QUALITY DATA FOR OCTOBER 1 AND 2, 1990

WELL I.D.	EV11-01	EV12-01	EV13-01	EV14-10
SAMPLE DATE	10/02/90	10/02/90	10/02/90	10/02/90
WATER QUALITY PARAMETER				
Temperature(°C)	9	8	10	9
Lab pH	7.34	7.15	7.48	7.10
Lab TDS(mg/L)	360	1000	540	540
Lab Cond.(mS)	0.97	0.80	0.53	1.60
Ca(mg/L)	46	151	63	122
Mg(mg/L)	21	48	29	47
Na(mg/L)	27.0	59.0	12.0	55.0
K(mg/L)	5.1	7.0	3.6	6.3
Fe(mg/L)	<.02	1.100	<.02	9.900
Mn(mg/L)	0.970	0.800	<.01	1.600
Nitrate(NO_3-N, mg/L)	5.0	<1	15.0	<1
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.082	0.412	0.069	0.297
HCO_3 ALK(mg/L)	248	531	237	350
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	203	435	194	287
SO_4(mg/L)	34	193	28	240
PO_4(mg/L)	<1	<1	<1	<1
CL(mg/L)	2.0	20.0	3.7	27.0
F(mg/L)	<1	<1	<1	<1
TOC(mg/L) - FILTERED	35.8	26.8	26.0	31.2
% Sodium	0.00	0.01	0.00	0.01
Calc. $CaCO_3$ ALK(mg/L)	207	444	198	293
Calc. TDS(mg/L)	405	1010	442	857
Calc. SAR	0.83	1.07	0.31	1.07
Calc. Hardness(mg/L)	201	575	277	498
Calc. Ion Balance(%)	-1.38	-3.64	-4.31	-6.30

WATER QUALITY DATA FOR OCTOBER 1 AND 2, 1990

WELL I.D.	EV15-01	EV16-01
SAMPLE DATE	10/02/90	10/02/90
WATER QUALITY PARAMETER		
Temperature(°C)	9	10
Lab pH	7.02	7.24
Lab TDS(mg/L)	420	680
Lab Cond.(mS)	1.30	0.80
Ca(mg/L)	56	128
Mg(mg/L)	22	45
Na(mg/L)	39.0	4.4
K(mg/L)	5.6	2.3
Fe(mg/L)	4.000	<.02
Mn(mg/L)	1.300	0.024
Nitrate(NO_3-N, mg/L)	<1	5.7
Nitrite(mg/L)	<1	<1
Ammonia(mg/L)	0.687	0.076
HCO_3 ALK(mg/L)	247	450
CO_3 ALK(mg/L)	0	0
$CaCO_3$ ALK(mg/L)	202	369
SO_4(mg/L)	84	65
PO_4(mg/L)	<1	<1
Cl(mg/L)	6.1	8.1
F(mg/L)	<1	<1
TOC(mg/L) - FILTERED	53.6	18.7
% Sodium	0.00	0.00
Calc. $CaCO_3$ ALK(mg/L)	207	376
Calc. TDS(mg/L)	464	728
Calc. SAR	1.12	0.09
Calc. Hardness(mg/L)	230	505
Calc. Ion Balance(%)	-5.47	-4.98

WATER QUALITY DATA FOR MAY 30, 1991

WELL I.D.	EV3-02	EV4-02	EV5-02	EV11-02
SAMPLE DATE	05/30/91	05/30/91	05/30/91	05/30/91
WATER QUALITY PARAMETER				
Temperature(°C)	9	10	9	9
Lab pH	7.33	7.35	7.28	7.64
Lab TDS(mg/L)	594	840	628	360
Ca(mg/L)	78.6	156	105	42.4
Mg(mg/L)	36.2	36.6	39	15.6
Na(mg/L)	37.3	47.5	38.5	27.9
K(mg/L)	7.7	7.8	7.9	5.7
Fe(mg/L)	1.7	4.6	8.3	<.2
Mn(mg/L)	2	0.7	1.5	0.4
Nitrate(NO_3-N, mg/L)	<1	<1	<1	2.3
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.29	0.73	0.23	0.19
HCO_3 ALK(mg/L)	375	439	406	243
CO_3 ALK(mg/L)	0	0	0	0
SO_4(mg/L)	126	274	168	15.6
Cl(mg/L)	12.5	24.3	27.2	2.8
TOC(mg/L) - FILTERED	32	42	42	34
TIC(mg/L) - FILTERED	152	127	145	127
TC(mg/L) - FILTERED	184	169	187	161
Field Diss. Oxy.(mg/L)	--	--	--	0.70
Calc. Ion Balance(%)	2.21	1.02	0.68	-0.7

WATER QUALITY DATA FOR MAY 30, 1991

WELL I.D.	EV12-02	EV13-02	EV14-02	EV15-02
SAMPLE DATE	05/30/91	05/30/91	05/30/91	05/30/91
WATER QUALITY PARAMETER				
Temperature(°C)	9	9	9	10
Lab pH	7.34	7.74	7.23	7.28
Lab TDS(mg/L)	860	454	808	398
Ca(mg/L)	137	55	108	43.5
Mg(mg/L)	34.6	22.2	35.8	15.3
Na(mg/L)	63.9	12.8	55.3	36.6
K(mg/L)	12.2	4.2	7.0	6.6
Fe(mg/L)	0.8	<.2	9	1.9
Mn(mg/L)	0.7	<.1	1.4	0.9
Nitrate(NO_3-N, mg/L)	<1	9.5	<1	<1
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.8	0.26	0.27	0.22
HCO_3 ALK(mg/L)	536	225	339	244
CO_3 ALK(mg/L)	0	0	0	0
SO_4(mg/L)	190	15.7	263	50.1
Cl(mg/L)	18.7	5.1	30.9	7.8
TOC(mg/L) - FILTERED	40	30	43	32
TIC(mg/L) - FILTERED	154	125	80	56
TC(mg/L) - FILTERED	194	155	123	88
Field Diss. Oxy.(mg/L)	0.10	2.34	0.61	0.41
Calc. Ion Balance(%)	1.72	0.44	2.14	-0.29

WATER QUALITY DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV1-03	EV2-03	EV3-03	EV4-03
SAMPLE DATE	09/24/91	09/24/91	09/24/91	09/24/91
WATER QUALITY PARAMETER				
Temperature(°C)	10	9	8	9
Lab pH	7.45	7.55	7.20	7.30
Lab Cond.(mS)	0.43	0.53	0.72	1.16
Ca(mg/L)	62	70	73	180
Mg(mg/L)	19	19	34	40
Na(mg/L)	1.8	20	37	50
K(mg/L)	1.6	3.7	7.2	7.5
Fe(mg/L)	<.2	<.2	1.7	4.3
Mn(mg/L)	<.1	0.59	1.5	0.81
Nitrate(NO_3-N, mg/L)	5.5	<1	<1	<1
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.40	0.63	0.14	0.95
HCO_3 ALK(mg/L)	234	274	366	497
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	192	224	300	408
SO_4(mg/L)	27	60	100	290
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	4.4	8	11	28
F(mg/L)	<1	<1	<1	<1
TOC(mg/L) - FILTERED	21	24	23	31
TIC(mg/L) - FILTERED	--	--	--	--
TC(mg/L) - FILTERED	--	--	--	--
TOC(mg/L) - UNFILTERED	--	--	--	--
TIC(mg/L) - UNFILTERED	--	--	--	--
TC(mg/L) - UNFILTERED	--	--	--	--
Field Diss. Oxy.(mg/L)	--	--	--	--
% Sodium	0.00	0.00	0.00	0.01
Calc. $CaCO_3$ ALK(mg/L)	196	229	306	416
Calc. TDS(mg/L)	373.8	454.7	632.5	1096.8
Calc. SAR	0.05	0.55	0.9	0.88
Calc. Hardness(mg/L)	233	253	322	614
Calc. Ion Balance(%)	1.36	-0.47	0.64	0.34

WATER QUALITY DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV5-03	EV6-03	EV7-03	EV8-03
SAMPLE DATE	09/24/91	09/24/91	09/24/91	09/24/91
WATER QUALITY PARAMETER				
Temperature(°C)	8	9	9	9
Lab pH	7.30	7.15	9.40	7.55
Lab Cond.(mS)	0.81	0.94	0.37	0.48
Ca(mg/L)	94	120	13	66
Mg(mg/L)	36	30	3.5	22
Na(mg/L)	42	54	60	4.4
K(mg/L)	7.1	8.2	11.0	2.1
Fe(mg/L)	6.8	1.3	<.2	<.2
Mn(mg/L)	1.4	0.57	<.1	<.1
Nitrate(NO_3-N, mg/L)	<1	<1	<1	11.1
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.36	0.62	0.07	0.11
HCO_3 ALK(mg/L)	413	450	62	242
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	339	369	104	198
SO_4(mg/L)	120	150	75	18
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	17	25	4.4	5.4
F(mg/L)	<1	<1	<1	<1
TOC(mg/L) - FILTERED	40	33	31	22
TIC(mg/L) - FILTERED	--	--	--	--
TC(mg/L) - FILTERED	--	--	--	--
TOC(mg/L) - UNFILTERED	--	--	--	--
TIC(mg/L) - UNFILTERED	--	--	--	--
TC(mg/L) - UNFILTERED	--	--	--	--
Field Diss. Oxy.(mg/L)	--	--	--	--
% Sodium	0.00	0.01	0.01	0.00
Calc. $CaCO_3$ ALK(mg/L)	345	376	105	202
Calc. TDS(mg/L)	735.9	838.5	260.9	408.9
Calc. SAR	0.93	1.14	3.81	0.12
Calc. Hardness(mg/L)	383	423	47	255
Calc. Ion Balance(%)	-1.42	0.53	-0.78	-0.62

WATER QUALITY DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV9-03	EV10-03	EV11-03	EV12-03
SAMPLE DATE	09/24/91	09/24/91	09/25/91	09/25/91
WATER QUALITY PARAMETER				
Temperature(°C)	9	9	9	9
Lab pH	7.45	7.50	7.72	7.50
Lab Cond.(mS)	0.60	0.49	0.44	1.08
Ca(mg/L)	74	64	44	140
Mg(mg/L)	18	25	17	38
Na(mg/L)	35	3.7	27	66
K(mg/L)	7.7	2.9	4.8	16.0
Fe(mg/L)	<.2	<.2	<.2	0.4
Mn(mg/L)	0.59	<.1	0.88	0.75
Nitrate(NO_3-N, mg/L)	<1	11.6	5.7	<1
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.32	<.05	0.07	0.61
HCO_3 ALK(mg/L)	295	219	238	540
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	242	180	195	443
SO_4(mg/L)	76	44	23	180
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	12	4.2	6.2	21
F(mg/L)	<1	<1	<1	<1
TOC(mg/L) - FILTERED	25	18	27	22
TIC(mg/L) - FILTERED	--	--	77	115
TC(mg/L) - FILTERED	--	--	104	137
TOC(mg/L) - UNFILTERED	--	--	26	22
TIC(mg/L) - UNFILTERED	--	--	73	119
TC(mg/L) - UNFILTERED	--	--	99	141
Field Diss. Oxy.(mg/L)	--	--	0.29	0.83
% Sodium	0.00	0.00	0.00	0.01
Calc. $CaCO_3$ ALK(mg/L)	247	183	199	451
Calc. TDS(mg/L)	517.7	413.8	385	1001.41
Calc. SAR	0.95	0.1	0.88	1.28
Calc. Hardness(mg/L)	259	263	180	506
Calc. Ion Balance(%)	-1.01	-0.36	0.67	-0.85

WATER QUALITY DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV13-03	EV14-03	EV15-03	EV16-03
SAMPLE DATE	09/25/91	09/25/91	09/25/91	09/25/91
WATER QUALITY PARAMETER				
Temperature(°C)	9	9	8	8
Lab pH	7.82	7.05	7.32	7.60
Lab Cond.(mS)	0.55	0.96	0.46	0.54
Ca(mg/L)	67	110	44	80
Mg(mg/L)	28	38	16	24
Na(mg/L)	10	54	37	3
K(mg/L)	3.0	6.8	5.9	1.0
Fe(mg/L)	<.2	11	4.6	<.2
Mn(mg/L)	<.1	1.4	0.88	<.1
Nitrate(NO_3-N, mg/L)	14.3	<1	<1	8.9
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.08	0.50	0.16	0.09
HCO_3 ALK(mg/L)	288	349	249	267
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	236	286	204	219
SO_4(mg/L)	20	250	42	38
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	8.6	26	8.6	10
F(mg/L)	<1	<1	<1	<1
TOC(mg/L) - FILTERED	11	45	40	31
TIC(mg/L) - FILTERED	69	97	69	--
TC(mg/L) - FILTERED	80	142	109	--
TOC(mg/L) - UNFILTERED	16	40	35	--
TIC(mg/L) - UNFILTERED	74	100	77	--
TC(mg/L) - UNFILTERED	90	140	112	--
Field Diss. Oxy.(mg/L)	7.12	0.37	0.22	--
% Sodium	0.00	0.01	0.00	0.00
Calc. $CaCO_3$ ALK(mg/L)	241	292	208	223
Calc. TDS(mg/L)	487.6	844.8	407.1	462
Calc. SAR	0.26	1.13	1.21	0.08
Calc. Hardness(mg/L)	283	431	176	299
Calc. Ion Balance(%)	1.88	-0.31	-3.00	-0.37

WATER QUALITY DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV17-03	EV18-03
SAMPLE DATE	09/25/91	09/25/91
WATER QUALITY PARAMETER		
Temperature(°C)	8	8
Lab pH	7.45	7.35
Lab Cond.(mS)	0.65	0.49
Ca(mg/L)	78	54
Mg(mg/L)	17	17
Na(mg/L)	41	29
K(mg/L)	6.5	4.1
Fe(mg/L)	0.8	2.7
Nitrate(NO_3-N, mg/L)	<1	<1
Nitrite(mg/L)	<1	<1
Ammonia(mg/L)	0.60	0.36
HCO_3 ALK(mg/L)	304	239
CO_3 ALK(mg/L)	0	0
$CaCO_3$ ALK(mg/L)	249	196
SO_4(mg/L)	95	67
PO_4(mg/L)	<1	<1
Cl(mg/L)	15	4.2
F(mg/L)	<1	<1
TOC(mg/L) - FILTERED	30	22
TIC(mg/L) - FILTERED	--	--
TC(mg/L) - FILTERED	--	--
TOC(mg/L) - UNFILTERED	--	--
TIC(mg/L) - UNFILTERED	--	--
TC(mg/L) - UNFILTERED	--	--
Field Diss. Oxy.(mg/L)	--	--
% Sodium	0.00	0.00
Calc. $CaCO_3$ ALK(mg/L)	254	200
Calc. TDS(mg/L)	557.25	417
Calc. SAR	1.1	0.88
Calc. Hardness(mg/L)	265	205
Calc. Ion Balance(%)	0.7	-1.58

WATER QUALITY DATA FOR JANUARY 22, 1992

WELL I.D.	EV3-04	EV4-04	EV5-04	EV11-04
SAMPLE DATE	01/22/92	01/22/92	01/22/92	01/22/92
WATER QUALITY PARAMETER				
Temperature(°C)	8	7	7	8
Lab pH	7.10	7.15	7.05	7.50
Lab Cond.(mS)	0.59	1.01	0.70	0.38
Ca(mg/L)	79	200	100	46
Mg(mg/L)	37	46	39	18
Na(mg/L)	36	50	43	26
K(mg/L)	7.3	7.8	7.8	5.3
Fe(mg/L)	3.7	6.0	8.4	<.2
Mn(mg/L)	1.4	0.85	1.5	1.2
Nitrate(NO_3-N, mg/L)	<1	<1	<1	3.4
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.07	0.69	0.23	<0.05
HCO_3 ALK(mg/L)	348	510	412	236
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	286	418	338	194
SO_4(mg/L)	97	280	120	18
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	11	31	18	3.7
TOC(mg/L) - FILTERED	38	49	39	37
TIC(mg/L) - FILTERED	108	126	123	73
TC(mg/L) - FILTERED	146	175	162	110
TOC(mg/L) - UNFILTERED	54	54	80	39
TIC(mg/L) - UNFILTERED	101	136	131	73
TC(mg/L) - UNFILTERED	155	190	211	112
Redox Potential (mV)	-11	-39	-86	158
Field Diss. Oxy.(mg/L)	--	--	--	0.45
% Sodium	0.00	0.01	0.00	0.00
Calc. Hardness $CaCO_3$(mg/L)	350	689	410	189
Calc. TDS(mg/L)	624.1	1130.8	748.2	372
Calc. SAR	0.84	0.83	0.92	0.82
Calc. Ion Balance(%)	-4.83	-4.44	-4.70	-4.02

WATER QUALITY DATA FOR JANUARY 22, 1992

WELL I.D.	EV12-04	EV13-04	EV14-04	EV15-04
SAMPLE DATE	01/22/92	01/22/92	01/22/92	01/22/92
WATER QUALITY PARAMETER				
Temperature(°C)	7	8	7	8
Lab pH	7.33	7.34	7.05	7.55
Lab Cond.(mS)	0.96	0.46	0.86	0.43
Ca(mg/L)	160	64	130	50
Mg(mg/L)	41	26	43	17
Na(mg/L)	57	11	51	34
K(mg/L)	10.0	3.6	7.1	6.3
Fe(mg/L)	1.3	<0.2	12	6
Mn(mg/L)	0.77	<0.1	1.6	0.93
Nitrate(NO_3-N, mg/L)	<1	15.8	<1	<1
Nitrite(mg/L)	<1	<1	<1	<1
Ammonia(mg/L)	0.83	<0.05	0.37	0.22
HCO_3 ALK(mg/L)	550	226	346	243
CO_3 ALK(mg/L)	0	0	0	0
$CaCO_3$ ALK(mg/L)	451	185	284	200
SO_4(mg/L)	190	14	240	43
PO_4(mg/L)	<1	<1	<1	<1
Cl(mg/L)	24	5.9	28	8.7
TOC(mg/L) - FILTERED	35	30	38	30
TIC(mg/L) - FILTERED	128	66	94	55
TC(mg/L) - FILTERED	163	96	132	85
TOC(mg/L) - UNFILTERED	42	40	44	33
TIC(mg/L) - UNFILTERED	129	78	95	75
TC(mg/L) - UNFILTERED	171	118	139	108
Redox Potential (mV)	-15	178	-75	-73
Field Diss. Oxy.(mg/L)	0.37	5.71	0.39	0.42
% Sodium	0.01	0.00	0.01	0.00
Calc. Hardness $CaCO_3$(mg/L)	568	267	502	195
Calc. TDS(mg/L)	1033.3	428.5	857.1	408
Calc. SAR	1.04	0.29	0.99	1.06
Calc. Ion Balance(%)	-1.86	-4.27	-6.58	-6.68

APPENDIX VIII

NITRATE DATA

Appendix VIII

Nitrate analysis was done on all water table wells and on well nest EV-11 to 15 to monitor temporal and spatial variability of nitrate. Because of the frequency of analysis, a Hach DR-100 colorimeter procedure was used. This method was verified with ion chromatography and nitrate results were found to compare favorably (±7 percent). Sample collection was by the procedures described in Appendix VII.

NITRATE (AS NITROGEN - mg/L)

DATE	10/02/90	10/25/90	11/14/90	12/05/90	01/22/91	03/14/91
WELL						
EV-1	8.0	8.7	11.0	10.9	--	13.1
EV-3	2.0	<1	<1	<1	--	<1
EV-8	11.4	9.0	8.8	8.0	--	7.4
EV-10	11.6	8.1	11.5	8.4	--	10.6
EV-13	15.0	10.9	10.8	4.8	11.3	15.5
EV-16	5.7	4.5	<1	3.5	3.1	4.5
EV-13	15.0	10.9	10.8	4.8	11.3	15.5
EV-11	5.0	4.1	5.0	5.5	6.0	4.9
EV-15	<1	<1	<1	<1	<1	<1
EV-14	<1	<1	<1	1.8	<1	<1
EV-12	<1	<1	<1	<1	<1	<1
EV-L1	--	--	--	--	--	--
EV-L2	--	--	--	--	--	--
EV-L3	--	--	--	--	--	--
EV-L4	--	--	--	--	--	--
EV-L5	--	--	--	--	--	--
EV-L6	--	--	--	--	--	--

DATE	04/09/91	04/24/91	05/09/91	05/30/91	06/19/91	07/10/91
WELL						
EV-1	9.9	7.9	8.8	3.7	5.1	3.0
EV-3	<1	<1	<1	<1	<1	<1
EV-8	--	7.6	8.2	1.4	8.1	9.6
EV-10	10.5	9.4	12.8	7.3	10.1	10.5
EV-13	20.9	15.6	14.0	9.5	10.7	11.0
EV-16	3.3	4.9	4.9	5.6	10.0	9.9
EV-13	20.9	15.6	14.0	9.5	10.7	11.0
EV-11	3.6	4.0	3.8	2.3	3.6	3.1
EV-15	<1	<1	<1	<1	<1	<1
EV-14	<1	<1	<1	<1	<1	<1
EV-12	<1	<1	<1	<1	<1	<1
EV-L1	--	--	--	--	--	--
EV-L2	--	--	--	--	--	--
EV-L3	--	--	--	--	--	18.7
EV-L4	--	--	--	--	--	11.7
EV-L5	--	--	--	--	--	--
EV-L6	--	--	--	--	--	--

NITRATE (AS NITROGEN - mg/L)

DATE	07/24/91	09/04/91	09/25/91	10/22/91	11/22/91	01/21/92
WELL						
EV-1	3.6	4	5.5	4	5.1	7.3
EV-3	<1	<1	<1	<1	<1	<1
EV-8	10.9	8.5	11.1	7.4	11.4	11.4
EV-10	8.8	8.9	11.6	7.4	9	7.6
EV-13	11.5	7.5	14.3	9.2	15.2	15.8
EV-16	9.4	7.6	8.9	6.7	11.2	12.6
EV-13	11.5	7.5	14.3	9.2	15.2	15.8
EV-11	4.1	3.7	5.7	3.5	3.7	3.4
EV-15	<1	<1	<1	<1	<1	<1
EV-14	<1	<1	<1	<1	<1	<1
EV-12	<1	<1	<1	<1	<1	<1
EV-L1	--	--	--	--	--	--
EV-L2	--	--	--	--	--	--
EV-L3	--	--	--	--	--	--
EV-L4	--	--	--	--	--	--
EV-L5	--	--	--	--	--	--
EV-L6	--	--	--	--	--	--

APPENDIX IX

DISSOLVED OXYGEN AND TEMPERATURE DATA

Appendix IX

Dissolved oxygen and temperature were measured within wells EV-11 to 15 using a YSI 5739 dissolved-oxygen probe and a YSI model 58 dissolved-oxygen meter. Measurements were made at the midpoint of the well screens.

DISSOLVED OXYGEN (mg/L)

DATE		10/25/90	11/14/90	12/05/90	01/22/91	03/14/91
WELL	DEPTH (metres)					
EV-13	7.01	6.77	6.23	3.99	7.51	7.95
EV-11	8.53	0.18	0.12	0.30	0.47	0.65
EV-15	10.06	0.19	--	0.28	0.23	0.27
EV-14	13.11	0.11	--	0.32	0.37	0.21
EV-12	19.20	0.19	--	0.08	0.33	0.08

TEMPERATURE (°C)

WELL	DEPTH (metres)					
EV-13	7.01	9.2	8.6	7.9	8.2	8.0
EV-11	8.53	7.6	7.6	9.0	8.8	7.8
EV-15	10.06	7.5	--	7.4	7.6	7.7
EV-14	13.11	7.5	--	7.3	7.2	7.4
EV-12	19.20	7.2	--	7.1	7.2	7.1

DISSOLVED OXYGEN (mg/L)

DATE		04/09/91	04/24/91	05/09/91	05/30/91	06/18/91
WELL	DEPTH (metres)					
EV-13	7.01	6.40	2.48	2.55	2.34	7.37
EV-11	8.53	0.60	0.79	0.61	0.70	0.55
EV-15	10.06	0.45	0.42	0.36	0.41	0.50
EV-14	13.11	0.43	0.47	0.34	0.61	0.42
EV-12	19.20	0.07	0.08	0.11	0.10	0.37

TEMPERATURE (°C)

WELL	DEPTH (metres)					
EV-13	7.01	8.6	7.6	7.6	8.8	7.8
EV-11	8.53	7.5	7.7	7.6	7.7	7.4
EV-15	10.06	7.7	7.7	7.7	7.7	7.6
EV-14	13.11	7.4	7.4	7.4	7.4	7.5
EV-12	19.20	7.1	7.1	7.3	7.2	7.2

DISSOLVED OXYGEN (mg/L)

DATE		07/09/91	07/23/91	09/04/91	09/25/91	10/22/91
WELL	DEPTH (metres)					
EV-13	7.01	7.96	8.54	7.88	7.12	5.92
EV-11	8.53	0.64	0.72	0.64	0.29	0.74
EV-15	10.06	0.67	0.60	--	0.22	0.36
EV-14	13.11	0.59	0.59	0.66	0.37	0.39
EV-12	19.20	0.49	0.61	0.44	0.83	0.38

TEMPERATURE (°C)

WELL	DEPTH (metres)					
EV-13	7.01	8.7	7.9	7.6	7.7	8.2
EV-11	8.53	7.5	7.3	7.6	7.3	7.4
EV-15	10.06	7.6	7.6	7.5	7.3	7.3
EV-14	13.11	7.5	7.6	7.4	7.4	7.3
EV-12	19.20	7.2	7.2	7.1	7.7	7.2

DISSOLVED OXYGEN (mg/L)

DATE		11/21/91	01/21/92
WELL	DEPTH (metres)		
EV-13	7.01	5.71	6.22
EV-11	8.53	0.41	0.45
EV-15	10.06	0.42	0.36
EV-14	13.11	0.39	0.30
EV-12	19.20	0.37	0.48

TEMPERATURE (°C)

WELL	DEPTH (metres)		
EV-13	7.01	8.3	7.6
EV-11	8.53	7.3	7.6
EV-15	10.06	7.2	7.4
EV-14	13.11	7.3	7.1
EV-12	19.20	7.1	7.1

APPENDIX X

ANALYTICAL METHODS AND PRESERVATION TECHNIQUES

Appendix X

All analyses with the exception of nitrate analysis by the colorimetric method, were performed by the Energy and Environmental Research Center Water Analysis Laboratory in compliance with quality assurance/quality control guidelines for the state of North Dakota. The following tables list the chemical parameter, preservation, analytical technique, standard method, and accuracy of the analyses. All samples from collection time to analysis were stored at 4°C, with holding times less than two weeks. Nitrate and nitrite samples were analyzed within 48 hours of collection.

Instruments

Cold Vapor AA - Perkin Elmer 5100 Atomic Adsorption Spectrometer.
Furnace AA - Perkin Elmer 5100 Atomic Adsorption Spectrometer.
Flame AA - Perkin Elmer 5100 Atomic Adsorption Spectrometer.
ICP - Leehman PS1000 Inductively Coupled Plasma Spectrometer.
IC - Dionex 2120i Ion Chromatograph.

Parameter	Preservation	Technique
pH	--	Corning pH meter
Lab TDS	--	180°C Dried-Analytical Balance
Lab Conductivity	--	Barnstead PM 70CB
Calcium	pH<2;HNO_3	ICP
Magnesium	pH<2;HNO_3	ICP
Sodium	pH<2;HNO_3	Flame AA
Potassium	pH<2;HNO_3	Flame AA
Iron	pH<2;HNO_3	ICP
Nitrate	--	IC
	--	Hach Dr-100 Colorimeter
Nitrite	--	IC
Ammonia	pH<2;HNO_3	Distillation/Electrode
HCO_3 Alkalinity	--	Titration
CO_3 Alkalinity	--	Titration
$CaCO_3$ Alkalinity	--	Titration
Sulfate	--	IC
Phosphate	--	IC
Chloride	--	IC
Fluoride	--	IC
Total Organic Carbon	--	Dohrmann DC-80
Total Inorganic Carbon	--	Dohrmann DC-80
Total Carbon	--	Dohrmann DC-80
Biological Oxygen Demand	--	5 Day - 20°C
Silver	pH<2;HNO_3	Furnace AA
Aluminum	pH<2;HNO_3	ICP
Arsenic	pH<2;HNO_3	Furnace AA
Boron	pH<2;HNO_3	ICP
Barium	pH<2;HNO_3	ICP
Bromide	--	IC
Cadmium	pH<2;HNO_3	Furnace AA
Chromium	pH<2;HNO_3	Furnace AA
Copper	pH<2;HNO_3	Furnace AA
Mercury	pH<2;HNO_3	Cold Vapor AA
Manganese	pH<2;HNO_3	ICP
Molybdenum	pH<2;HNO_3	ICP
Nickel	pH<2;HNO_3	ICP
Lead	pH<2;HNO_3	Furnace AA
Selenium	pH<2;HNO_3	Furnace AA
Silicon	pH<2;HNO_3	ICP
Strontium	pH<2;HNO_3	ICP
Zinc	pH<2;HNO_3	ICP
Vanadium	pH<2;HNO_3	ICP

Parameter	Method	Accuracy (+/-)
pH	SM 423	0.1 pH units
Lab TDS	SM 209B	5 percent
Lab Conductivity	EPA 120.1	5 percent
Calcium	EPA 200.7	3 percent
Magnesium	EPA 200.7	3 percent
Sodium	EPA 273.1	2 percent
Potassium	EPA 258.1	2 percent
Iron	EPA 200.7	3 percent
Nitrate	EPA 300.0	5 percent
	Not Approved	
Nitrite	EPA 300.0	5 percent
Ammonia	SM 417A/417E	5 percent
HCO_3 Alkalinity	EPA 310.1	3 percent
CO_3 Alkalinity	EPA 310.1	3 percent
$CaCO_3$ Alkalinity	EPA 310.1	3 percent
Sulfate	EPA 300.0	5 percent
Phosphate	EPA 300.0	5 percent
Chloride	EPA 300.0	5 percent
Fluoride	EPA 300.0	5 percent
Total Organic Carbon	SM 505A	2 percent
Total Inorganic Carbon	SM 505A	2 percent
Total Carbon	SM 505A	2 percent
Biological Oxygen Demand	EPA 405.1	18 percent
Silver	EPA 272.2	10 percent
Aluminum	EPA 200.7	5 percent
Arsenic	EPA 206.2	10 percent
Boron	Not Approved	5 percent
Barium	EPA 200.7	5 percent
Bromide	EPA 300.0	5 percent
Cadmium	EPA 213.2	10 percent
Chromium	EPA 218.2	10 percent
Copper	EPA 220.2	10 percent
Mercury	EPA 245.1	5 percent
Manganese	EPA 200.7	5 percent
Molybdenum	EPA 200.7	5 percent
Nickel	EPA 200.7	5 percent
Lead	EPA 239.2	10 percent
Selenium	EPA 270.2	10 percent
Silicon	EPA 200.7	5 percent
Strontium	EPA 200.7	5 percent
Zinc	EPA 200.7	5 percent
Vanadium	EPA 200.7	5 percent

APPENDIX XI

TRACE METAL DATA

Appendix XI

Trace metal data were collected on three dates, October 1990 and May and September 1991. Sample collection procedures are described in Appendix VII and methods of analyses in Appendix X.

ABBREVIATIONS

Ag = Silver
Al = Aluminum
As = Arsenic
B = Boron
Ba = Barium
Br = Bromide
Cd = Cadmium
Cr = Chromium
Cu = Copper
Hg = Mercury
Mo = Molybdenum
Ni = Nickel
Pb = Lead
Se = Selenium
Si = Silicon
Sr = Strontium
Zn = Zinc
V = Vanadium

TRACE METAL DATA FOR OCTOBER 1 AND 2, 1990

WELL I.D.	EV1-01	EV3-01	EV8-01	EV10-01
SAMPLE DATE	10/01/90	10/01/90	10/02/90	10/01/90
Metals				
Ag(ug/L)	<1	<1	<1	<1
Al(mg/L)	<.2	<.2	<.2	<.2
As(ug/L)	<3	<3	<3	15.7
B(mg/L)	<.05	<.05	<.05	<.05
Ba(mg/L)	0.015	0.104	0.029	0.032
Br(mg/L)	<1	<1	<1	<1
Cd(mg/L)	<.01	<.01	<.01	<.01
Cr(mg/L)	<.01	<.01	<.01	<.01
Cu(mg/L)	<.01	<.01	<.01	<.01
Hg(ug/L)	<3	<3	<3	<3
Mo(mg/L)	0.030	0.046	0.034	0.028
Ni(mg/L)	<.02	<.02	<.02	<.02
Pb(ug/L)	<10	<10	<10	<10
Se(ug/L)	<3	<3	<3	<3
Si(mg/L)	14	12	15	15
Sr(mg/L)	0.067	0.165	0.087	0.097
Zn(mg/L)	0.011	0.015	<.01	<.01
V(mg/L)	<.01	<.01	<.01	<.01

WELL I.D.	EV11-01	EV12-01	EV13-01	EV14-10
SAMPLE DATE	10/02/90	10/02/90	10/02/90	10/02/90
Metals				
Ag(ug/L)	<1	<1	<1	<1
Al(mg/L)	<.2	<.2	<.2	<.2
As(ug/L)	<3	17.9	<3	<3
B(mg/L)	<.05	0.083	<.05	<.05
Ba(mg/L)	0.230	0.048	0.019	0.270
Br(mg/L)	<1	<1	<1	<1
Cd(mg/L)	<.01	<.01	<.01	<.01
Cr(mg/L)	<.01	<.01	<.01	<.01
Cu(mg/L)	<.01	<.01	<.01	<.01
Hg(ug/L)	<3	<3	<3	<3
Mo(mg/L)	0.029	0.096	0.043	0.058
Ni(mg/L)	0.021	0.026	<.02	0.035
Pb(ug/L)	<10	<10	<10	<10
Se(ug/L)	<3	<3	<3	<3
Si(mg/L)	12	13	14	14
Sr(mg/L)	0.081	0.610	0.109	0.310
Zn(mg/L)	<.01	0.013	<.01	<.01
V(mg/L)	<.01	<.01	<.01	<.01

TRACE METAL DATA FOR OCTOBER 1 AND 2, 1990

WELL I.D.	EV15-01	EV16-01
SAMPLE DATE	10/02/90	10/02/90
Metals		
Ag(ug/L)	<1	<1
Al(mg/L)	<.2	<.2
As(ug/L)	5.4	<3
B(mg/L)	<.05	<.05
Ba(mg/L)	0.200	0.080
Br(mg/L)	<1	<1
Cd(mg/L)	<.01	<.01
Cr(mg/L)	<.01	<.01
Cu(mg/L)	<.01	<.01
Hg(ug/L)	<3	<3
Mo(mg/L)	0.024	0.060
Ni(mg/L)	<.02	<.02
Pb(ug/L)	<10	<10
Se(ug/L)	<3	<3
Si(mg/L)	14	14
Sr(mg/L)	0.110	0.170
Zn(mg/L)	<.01	<.01
V(mg/L)	<.01	<.01

TRACE METAL DATA FOR MAY 30, 1991

WELL I.D.	EV3-02	EV4-02	EV5-02	EV11-02
SAMPLE DATE	05/30/91	05/30/91	05/30/91	05/30/91
Metals				
As(ug/L)	<10	<10	<10	<10
Cr(mg/L)	<.1	<.1	<.1	<.1
Cu(mg/L)	<.1	<.1	<.1	<.1
Ni(mg/L)	<.2	<.2	<.2	<.2

WELL I.D.	EV12-02	EV13-02	EV14-02	EV15-02
SAMPLE DATE	05/30/91	05/30/91	05/30/91	05/30/91
Metals				
As(ug/L)	<10	20	<10	<10
Cr(mg/L)	<.1	<.1	<.1	<.1
Cu(mg/L)	<.1	<.1	<.1	<.1
Ni(mg/L)	<.2	<.2	<.2	<.2

TRACE METAL DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV1-03	EV2-03	EV3-03	EV4-03
SAMPLE DATE	09/24/91	09/24/91	09/24/91	09/24/91
Metals				
Al(mg/L)	<1	<1	<1	<1
As(ug/L)	<10	17	<10	11
B(mg/L)	<.2	<.2	<.2	<.2
Br(mg/L)	<1	<1	<1	<1
Mo(mg/L)	<.1	<.1	<.1	<.1
Se(ug/L)	<10	<10	<10	<10
Si(mg/L)	13	13	12	13
Sr(mg/L)	<.5	<.5	<.5	0.66

WELL I.D.	EV5-03	EV6-03	EV7-03	EV8-03
SAMPLE DATE	09/24/91	09/24/91	09/24/91	09/24/91
Metals				
Al(mg/L)	<1	<1	<1	<1
As(ug/L)	<10	18	<10	<10
B(mg/L)	<.2	<.2	<.2	<.2
Br(mg/L)	<1	<1	<1	<1
Mo(mg/L)	<.1	<.1	<.1	<.1
Se(ug/L)	<10	<10	<10	<10
Si(mg/L)	14	13	26	14
Sr(mg/L)	<.5	0.59	<.5	<.5

WELL I.D.	EV9-03	EV10-03	EV11-03	EV12-03
SAMPLE DATE	09/24/91	09/24/91	09/25/91	09/25/91
Metals				
Al(mg/L)	<1	<1	<1	<1
As(ug/L)	17	<10	<10	13
B(mg/L)	<.2	<.2	<.2	<.2
Br(mg/L)	<1	<1	<1	<1
Mo(mg/L)	<.1	<.1	<.1	<.1
Se(ug/L)	<10	<10	<10	<10
Si(mg/L)	13	13	13	14
Sr(mg/L)	<.5	<.5	<.5	0.63

TRACE METAL DATA FOR SEPTEMBER 24 AND 25, 1991

WELL I.D.	EV13-03	EV14-03	EV15-03	EV16-03
SAMPLE DATE	09/25/91	09/25/91	09/25/91	09/25/91
Metals				
Al(mg/L)	<1	<1	<1	<1
As(ug/L)	<10	<10	10	<10
B(mg/L)	<.2	<.2	<.2	<.2
Br(mg/L)	<1	<1	<1	<1
Mo(mg/L)	<.1	<.1	<.1	<.1
Se(ug/L)	<10	<10	<10	<10
Si(mg/L)	14	13	13	14
Sr(mg/L)	<.5	<.5	<.5	<.5

WELL I.D.	EV17-03	EV18-03
SAMPLE DATE	09/25/91	09/25/91
Metals		
Al(mg/L)	<1	<1
As(ug/L)	14	<10
B(mg/L)	<.2	<.2
Br(mg/L)	<1	<1
Mo(mg/L)	<.1	<.1
Se(ug/L)	<10	<10
Si(mg/L)	14	14
Sr(mg/L)	<.5	<.5

APPENDIX XII

PARTICLE SIZE DISTRIBUTION DATA

Appendix XII

Particle size distribution data (ASTM, 1985) was obtained from sieve and hydrometer analysis of split-spoon samples collected during well installation.

EV-14 (0-0.6 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	24.80	24.80	84.54
0.4500	44.80	69.60	56.61
0.3000	42.30	111.90	30.24
0.1800	17.30	129.20	19.46
0.1500	14.50	143.70	10.42
0.1060	6.70	150.40	6.24
0.0680	8.40	158.80	1.00
0.0481	0.00	158.80	1.00
0.0340	0.00	158.80	1.00
0.0215	0.00	158.80	1.00
0.0125	0.32	159.12	0.80
0.0088	0.11	159.23	0.74
0.0063	0.32	159.55	0.54
0.0031	0.54	160.09	0.20
0.0013	0.32	160.41	0.00

EV-14 (0.6-1.2 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	32.60	32.60	83.08
0.4500	61.60	94.20	51.11
0.3000	53.60	147.80	23.29
0.1800	25.40	173.20	10.11
0.1500	3.50	176.70	8.29
0.1060	5.90	182.60	5.23
0.0680	8.58	191.18	0.77
0.0481	0.11	191.29	0.72
0.0340	0.11	191.40	0.66
0.0215	0.00	191.40	0.66
0.0125	0.33	191.73	0.49
0.0088	0.00	191.73	0.49
0.0063	0.51	192.24	0.22
0.0031	0.40	192.64	0.02
0.0013	0.03	192.67	0.00

EV-14 (1.2-1.8 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	27.20	27.20	81.16
0.4500	44.50	71.70	50.34
0.3000	42.90	114.60	20.62
0.1800	16.40	131.00	9.26
0.1500	2.10	133.10	7.81
0.1060	3.50	136.60	5.38
0.0680	6.80	143.40	0.67
0.0481	0.08	143.48	0.62
0.0340	0.08	143.56	0.56
0.0215	0.08	143.64	0.51
0.0125	0.08	143.72	0.45
0.0088	0.08	143.80	0.39
0.0063	0.24	144.04	0.23
0.0031	0.16	144.21	0.11
0.0013	0.16	144.37	0.00

EV-14 (1.8-2.4 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	23.40	23.40	79.01
0.4500	36.00	59.40	46.73
0.3000	31.90	91.30	18.12
0.1800	13.30	104.60	6.19
0.1500	1.30	105.90	5.02
0.1060	2.40	108.30	2.87
0.0680	2.87	111.17	0.30
0.0481	0.03	111.20	0.27
0.0340	0.02	111.22	0.25
0.0215	0.03	111.25	0.22
0.0125	0.02	111.27	0.21
0.0088	0.07	111.34	0.15
0.0063	0.03	111.37	0.12
0.0031	0.10	111.47	0.03
0.0013	0.03	111.50	0.00

EV-14 (2.4-3.0 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	17.70	17.70	85.64
0.4500	34.20	51.90	57.88
0.3000	30.80	82.70	32.89
0.1800	25.30	108.00	12.36
0.1500	3.40	111.40	9.60
0.1060	4.50	115.90	5.95
0.0680	5.85	121.75	1.20
0.0481	0.16	121.91	1.07
0.0340	0.08	121.98	1.01
0.0215	0.16	122.14	0.88
0.0125	0.35	122.49	0.60
0.0088	0.12	122.61	0.50
0.0063	0.16	122.76	0.38
0.0031	0.35	123.12	0.09
0.0013	0.12	123.23	0.00

EV-14 (3.0-3.7 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	20.10	20.10	86.23
0.4500	30.00	50.10	65.69
0.3000	31.50	81.60	44.12
0.1800	45.20	126.80	13.16
0.1500	4.80	131.60	9.88
0.1060	5.50	137.10	6.11
0.0680	7.69	144.79	0.84
0.0481	0.10	144.89	0.78
0.0340	0.05	144.93	0.75
0.0215	0.24	145.17	0.58
0.0125	0.24	145.41	0.42
0.0088	0.10	145.50	0.36
0.0063	0.10	145.60	0.29
0.0031	0.29	145.88	0.10
0.0013	0.14	146.02	0.00

EV-14 (3.7-4.3 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	41.00	41.00	73.58
0.4500	51.40	92.40	40.47
0.3000	28.40	120.80	22.17
0.1800	17.10	137.90	11.15
0.1500	3.30	141.20	9.03
0.1060	4.80	146.00	5.93
0.0680	8.20	154.20	0.65
0.0481	0.05	154.25	0.62
0.0340	0.19	154.44	0.50
0.0215	0.00	154.44	0.50
0.0125	0.19	154.63	0.37
0.0088	0.10	154.73	0.31
0.0063	0.19	154.92	0.19
0.0031	0.10	155.02	0.12
0.0013	0.19	155.21	0.00

EV-14 (4.3-4.9 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	46.50	46.50	71.79
0.4500	59.00	105.50	35.99
0.3000	35.80	141.30	14.26
0.1800	12.00	153.30	6.98
0.1500	2.40	155.70	5.53
0.1060	1.90	157.60	4.37
0.0680	6.54	164.14	0.41
0.0481	0.07	164.21	0.36
0.0340	0.04	164.25	0.34
0.0215	0.11	164.36	0.27
0.0125	0.04	164.40	0.25
0.0088	0.04	164.44	0.23
0.0063	0.11	164.55	0.16
0.0031	0.22	164.77	0.02
0.0013	0.04	164.81	0.00

EV-14 (4.9-5.5 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	24.00	24.00	63.70
0.4500	21.80	45.80	30.73
0.3000	12.50	58.30	11.83
0.1800	4.10	62.40	5.63
0.1500	0.60	63.00	4.72
0.1060	1.10	64.10	3.06
0.0680	1.81	65.91	0.32
0.0481	0.02	65.93	0.29
0.0340	0.02	65.95	0.26
0.0215	0.00	65.95	0.26
0.0125	0.02	65.97	0.23
0.0088	0.04	66.01	0.16
0.0063	0.02	66.03	0.13
0.0031	0.04	66.07	0.07
0.0013	0.04	66.12	0.01

EV-14 (5.5-6.1 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	35.10	35.10	51.73
0.4500	18.90	54.00	25.74
0.3000	7.50	61.50	15.43
0.1800	6.20	67.70	6.90
0.1500	1.10	68.80	5.39
0.1060	1.40	70.20	3.47
0.0680	2.26	72.46	0.35
0.0481	0.03	72.49	0.32
0.0340	0.00	72.49	0.32
0.0215	0.05	72.54	0.25
0.0125	0.03	72.57	0.21
0.0088	0.04	72.61	0.16
0.0063	0.04	72.64	0.10
0.0031	0.03	72.67	0.07
0.0013	0.05	72.72	0.00

EV-14 (6.1-6.7 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	37.40	37.40	47.62
0.4500	16.80	54.20	24.09
0.3000	6.90	61.10	14.43
0.1800	5.40	66.50	6.86
0.1500	0.90	67.40	5.60
0.1060	1.30	68.70	3.78
0.0680	2.49	71.19	0.29
0.0481	0.03	71.22	0.25
0.0340	0.01	71.23	0.23
0.0215	0.04	71.28	0.17
0.0125	0.00	71.28	0.17
0.0088	0.03	71.30	0.13
0.0063	0.03	71.33	0.10
0.0031	0.06	71.39	0.02
0.0013	0.01	71.40	0.00

EV-14 (6.7-7.3 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	39.00	39.00	48.34
0.4500	17.30	56.30	25.43
0.3000	7.80	64.10	15.10
0.1800	6.40	70.50	6.62
0.1500	1.00	71.50	5.30
0.1060	1.50	73.00	3.31
0.0680	2.31	75.31	0.25
0.0481	0.03	75.34	0.21
0.0340	0.01	75.35	0.19
0.0215	0.00	75.35	0.19
0.0125	0.04	75.39	0.14
0.0088	0.04	75.43	0.09
0.0063	0.01	75.44	0.07
0.0031	0.04	75.48	0.02
0.0013	0.01	75.50	0.01

EV-14 (7.3-7.9 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	21.00	21.00	65.83
0.4500	20.10	41.10	33.12
0.3000	9.70	50.80	17.33
0.1800	6.50	57.30	6.75
0.1500	1.10	58.40	4.96
0.1060	1.40	59.80	2.69
0.0680	1.53	61.33	0.20
0.0481	0.03	61.36	0.15
0.0340	0.01	61.36	0.14
0.0215	0.02	61.38	0.11
0.0125	0.01	61.39	0.10
0.0088	0.01	61.40	0.09
0.0063	0.01	61.40	0.07
0.0031	0.03	61.43	0.03
0.0013	0.03	61.45	-0.01

EV-14 (7.9-8.5 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	30.40	30.40	51.88
0.4500	16.40	46.80	25.93
0.3000	9.20	56.00	11.36
0.1800	4.70	60.70	3.93
0.1500	0.60	61.30	2.98
0.1060	0.90	62.20	1.55
0.0680	0.91	63.11	0.12
0.0481	0.02	63.12	0.09
0.0340	0.01	63.13	0.09
0.0215	0.00	63.13	0.09
0.0125	0.01	63.14	0.07
0.0088	0.01	63.15	0.06
0.0063	0.02	63.16	0.03
0.0031	0.01	63.17	0.02
0.0013	0.02	63.18	0.00

EV-14 (8.5-9.1 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	13.90	13.90	76.29
0.4500	17.70	31.60	46.10
0.3000	12.20	43.80	25.29
0.1800	8.70	52.50	10.46
0.1500	1.10	53.60	8.58
0.1060	2.10	55.70	5.00
0.0680	2.70	58.40	0.39
0.0481	0.03	58.43	0.34
0.0340	0.03	58.46	0.29
0.0215	0.00	58.46	0.29
0.0125	0.00	58.46	0.29
0.0088	0.03	58.49	0.24
0.0063	0.03	58.52	0.19
0.0031	0.05	58.57	0.11
0.0013	0.06	58.63	0.01

EV-14 (9.1-9.8 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	14.70	14.70	76.66
0.4500	23.40	38.10	39.49
0.3000	14.90	53.00	15.83
0.1800	6.60	59.60	5.35
0.1500	1.00	60.60	3.76
0.1060	1.10	61.70	2.02
0.0680	1.21	62.91	0.10
0.0481	0.01	62.92	0.08
0.0340	0.00	62.92	0.08
0.0215	0.01	62.94	0.06
0.0125	0.00	62.94	0.06
0.0088	0.01	62.95	0.03
0.0063	0.00	62.95	0.03
0.0031	0.01	62.95	0.03
0.0013	0.02	62.97	0.00

EV-14 (9.8-10.4 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	26.30	26.30	55.51
0.4500	18.60	44.90	24.04
0.3000	9.10	54.00	8.64
0.1800	3.50	57.50	2.72
0.1500	0.04	57.54	2.66
0.1060	0.09	57.63	2.50
0.0680	1.36	58.99	0.21
0.0481	0.02	59.00	0.18
0.0340	0.01	59.01	0.17
0.0215	0.02	59.02	0.15
0.0125	0.02	59.04	0.12
0.0088	0.00	59.04	0.12
0.0063	0.02	59.06	0.08
0.0031	0.01	59.07	0.07
0.0013	0.04	59.11	0.01

EV-14 (10.4-11.0 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	25.70	25.70	75.01
0.4500	34.50	60.20	41.47
0.3000	23.60	83.80	18.52
0.1800	10.50	94.30	8.31
0.1500	1.60	95.90	6.76
0.1060	2.70	98.60	4.13
0.0680	3.92	102.52	0.32
0.0481	0.04	102.56	0.28
0.0340	0.04	102.60	0.24
0.0215	0.04	102.65	0.20
0.0125	0.02	102.67	0.18
0.0088	0.00	102.67	0.18
0.0063	0.04	102.71	0.13
0.0031	0.09	102.80	0.05
0.0013	0.04	102.85	0.00

EV-14 (11.0-11.6 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	8.70	8.70	86.81
0.4500	28.90	37.60	42.98
0.3000	18.30	55.90	15.23
0.1800	6.60	62.50	5.22
0.1500	0.90	63.40	3.85
0.1060	1.10	64.50	2.18
0.0680	1.37	65.87	0.11
0.0481	0.02	65.88	0.09
0.0340	0.00	65.88	0.09
0.0215	0.01	65.89	0.08
0.0125	0.01	65.89	0.07
0.0088	0.00	65.89	0.07
0.0063	0.02	65.91	0.05
0.0031	0.02	65.93	0.01
0.0013	0.01	65.94	0.00

EV-14 (11.6-12.2 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	21.50	21.50	58.37
0.4500	13.70	35.20	31.84
0.3000	10.00	45.20	12.47
0.1800	4.00	49.20	4.73
0.1500	0.70	49.90	3.37
0.1060	0.70	50.60	2.01
0.0680	0.96	51.56	0.16
0.0481	0.01	51.57	0.14
0.0340	0.01	51.58	0.12
0.0215	0.00	51.58	0.12
0.0125	0.03	51.61	0.07
0.0088	0.00	51.61	0.07
0.0063	0.01	51.62	0.04
0.0031	0.02	51.63	0.01
0.0013	0.01	51.64	-0.01

EV-14 (12.2-12.8 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	38.60	38.60	49.63
0.4500	18.90	57.50	24.97
0.3000	11.80	69.30	9.58
0.1800	4.10	73.40	4.23
0.1500	0.40	73.80	3.71
0.1060	1.30	75.10	2.01
0.0680	1.40	76.50	0.18
0.0481	0.01	76.51	0.17
0.0340	0.02	76.52	0.15
0.0215	0.02	76.54	0.13
0.0125	0.01	76.55	0.12
0.0088	0.01	76.56	0.11
0.0063	0.02	76.57	0.09
0.0031	0.06	76.63	0.02
0.0013	0.01	76.64	0.01

EV-14 (12.8-13.4 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	29.50	29.50	62.48
0.4500	26.50	56.00	28.78
0.3000	11.70	67.70	13.90
0.1800	3.90	71.60	8.94
0.1500	1.40	73.00	7.16
0.1060	3.90	76.90	2.20
0.0680	1.61	78.51	0.15
0.0481	0.01	78.52	0.14
0.0340	0.01	78.53	0.13
0.0215	0.02	78.55	0.11
0.0125	0.01	78.56	0.09
0.0088	0.00	78.56	0.09
0.0063	0.03	78.58	0.06
0.0031	0.05	78.63	0.00
0.0013	0.00	78.63	0.00

EV-14 (13.4-14.0 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	21.30	21.30	76.99
0.4500	30.80	52.10	43.72
0.3000	25.60	77.70	16.07
0.1800	8.00	85.70	7.43
0.1500	1.00	86.70	6.35
0.1060	2.00	88.70	4.19
0.0680	3.52	92.22	0.39
0.0481	0.06	92.28	0.32
0.0340	0.04	92.32	0.28
0.0215	0.06	92.38	0.22
0.0125	0.00	92.38	0.22
0.0088	0.02	92.40	0.19
0.0063	0.02	92.42	0.17
0.0031	0.14	92.56	0.02
0.0013	0.02	92.58	0.00

EV-14 (14.0-14.6 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	23.00	23.00	55.46
0.4500	14.30	37.30	27.77
0.3000	8.30	45.60	11.70
0.1800	3.50	49.10	4.92
0.1500	1.00	50.10	2.98
0.1060	0.20	50.30	2.59
0.0680	1.23	51.53	0.21
0.0481	0.01	51.54	0.20
0.0340	0.02	51.56	0.15
0.0215	0.01	51.57	0.13
0.0125	0.01	51.59	0.10
0.0088	0.01	51.60	0.09
0.0063	0.02	51.62	0.05
0.0031	0.02	51.64	0.01
0.0013	0.01	51.64	-0.01

EV-14 (14.6-15.2 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	13.30	13.30	72.48
0.4500	17.40	30.70	36.48
0.3000	11.30	42.00	13.10
0.1800	3.80	45.80	5.23
0.1500	0.40	46.20	4.41
0.1060	0.80	47.00	2.75
0.0680	1.20	48.20	0.26
0.0481	0.02	48.23	0.22
0.0340	0.01	48.23	0.20
0.0215	0.02	48.25	0.16
0.0125	0.01	48.26	0.14
0.0088	0.03	48.29	0.09
0.0063	0.02	48.31	0.04
0.0031	0.01	48.32	0.03
0.0013	0.01	48.33	0.00

EV-14 (15.2-15.9 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	26.10	26.10	47.27
0.4500	11.00	37.10	25.05
0.3000	5.90	43.00	13.13
0.1800	3.80	46.80	5.45
0.1500	0.40	47.20	4.65
0.1060	0.80	48.00	3.03
0.0680	1.31	49.31	0.38
0.0481	0.03	49.34	0.32
0.0340	0.02	49.36	0.28
0.0215	0.02	49.38	0.25
0.0125	0.03	49.41	0.19
0.0088	0.00	49.41	0.19
0.0063	0.05	49.46	0.09
0.0031	0.02	49.47	0.06
0.0013	0.03	49.50	-0.01

EV-14 (15.9-16.5 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	2.10	2.10	96.80
0.4500	9.40	11.50	82.46
0.3000	16.00	27.50	58.07
0.1800	20.90	48.40	26.20
0.1500	5.20	53.60	18.27
0.1060	7.40	61.00	6.98
0.0680	3.92	64.92	1.01
0.0481	0.05	64.97	0.93
0.0340	0.05	65.02	0.86
0.0215	0.05	65.07	0.78
0.0125	0.15	65.21	0.56
0.0088	0.05	65.26	0.48
0.0063	0.15	65.41	0.26
0.0031	0.07	65.48	0.15
0.0013	0.10	65.58	0.00

EV-14 (16.5-17.1 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	1.40	1.40	96.62
0.4500	6.90	8.30	79.94
0.3000	12.00	20.30	50.93
0.1800	10.80	31.10	24.82
0.1500	2.80	33.90	18.06
0.1060	4.10	38.00	8.15
0.0680	2.66	40.66	1.71
0.0481	0.07	40.74	1.53
0.0340	0.05	40.79	1.40
0.0215	0.09	40.88	1.18
0.0125	0.13	41.01	0.88
0.0088	0.07	41.08	0.71
0.0063	0.07	41.15	0.53
0.0031	0.13	41.28	0.23
0.0013	0.09	41.37	0.01

EV-14 (17.1-17.7 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	3.10	3.10	93.52
0.4500	14.50	17.60	63.19
0.3000	13.60	31.20	34.74
0.1800	9.80	41.00	14.24
0.1500	1.40	42.40	11.32
0.1060	2.40	44.80	6.30
0.0680	2.28	47.08	1.53
0.0481	0.03	47.11	1.46
0.0340	0.03	47.15	1.38
0.0215	0.10	47.25	1.17
0.0125	0.14	47.39	0.89
0.0088	0.14	47.52	0.60
0.0063	0.14	47.66	0.32
0.0031	0.14	47.79	0.03
0.0013	0.02	47.81	0.00

EV-14 (17.7-18.3 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	4.90	4.90	88.01
0.4500	9.90	14.80	63.78
0.3000	11.50	26.30	35.63
0.1800	8.70	35.00	14.34
0.1500	1.40	36.40	10.92
0.1060	2.50	38.90	4.80
0.0680	1.60	40.50	0.88
0.0481	0.04	40.54	0.78
0.0340	0.02	40.56	0.73
0.0215	0.08	40.65	0.52
0.0125	0.06	40.71	0.37
0.0088	0.02	40.73	0.32
0.0063	0.01	40.74	0.29
0.0031	0.07	40.82	0.11
0.0013	0.04	40.86	0.00

EV-14 (18.3-18.9 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	9.50	9.50	83.55
0.4500	16.30	25.80	55.33
0.3000	14.90	40.70	29.54
0.1800	9.80	50.50	12.57
0.1500	1.80	52.30	9.45
0.1060	2.50	54.80	5.12
0.0680	2.37	57.17	1.02
0.0481	0.03	57.20	0.96
0.0340	0.08	57.28	0.83
0.0215	0.08	57.36	0.69
0.0125	0.08	57.44	0.56
0.0088	0.05	57.48	0.48
0.0063	0.05	57.53	0.40
0.0031	0.09	57.62	0.24
0.0013	0.14	57.76	-0.01

EV-14 (18.9-19.5 metres)

SIZE (mm)	WEIGHT RETAINED(g)	SUM WEIGHT RETAINED(g)	PERCENT PASSING
1.1800	0.00	0.00	100.00
0.6000	14.30	14.30	84.33
0.4500	12.00	26.30	71.19
0.3000	5.90	32.20	64.72
0.1800	6.20	38.40	57.93
0.1500	1.10	39.50	56.73
0.1060	6.40	45.90	49.72
0.0680	30.61	76.51	16.18
0.0481	3.22	79.73	12.65
0.0340	3.22	82.95	9.12
0.0215	3.76	86.71	5.00
0.0125	2.15	88.86	2.65
0.0088	0.54	89.40	2.06
0.0063	1.07	90.47	0.89
0.0031	0.54	91.01	0.30
0.0013	0.27	91.28	0.00

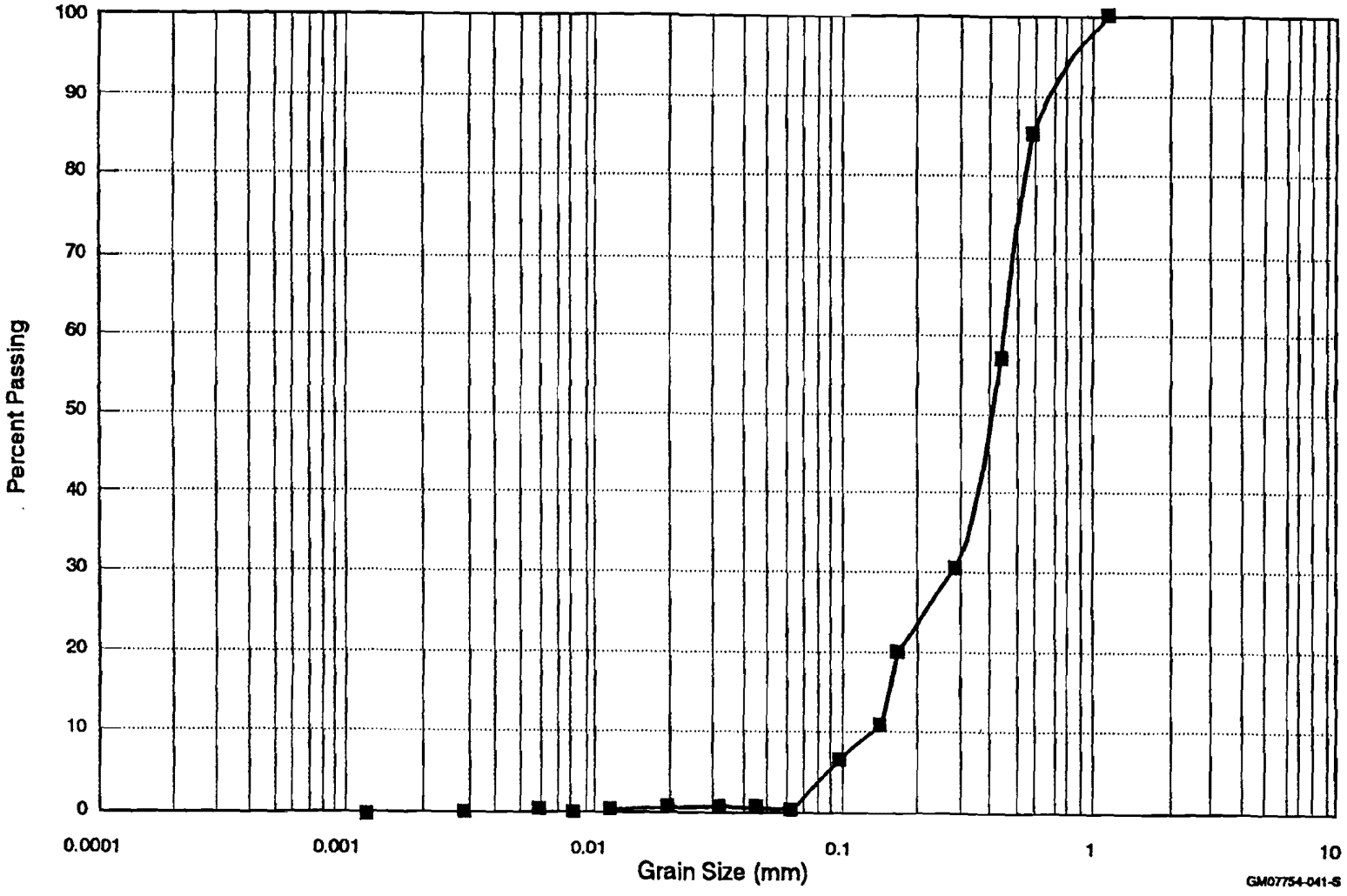


Figure 27. Grain size distribution curve (0 to 0.6 metres).

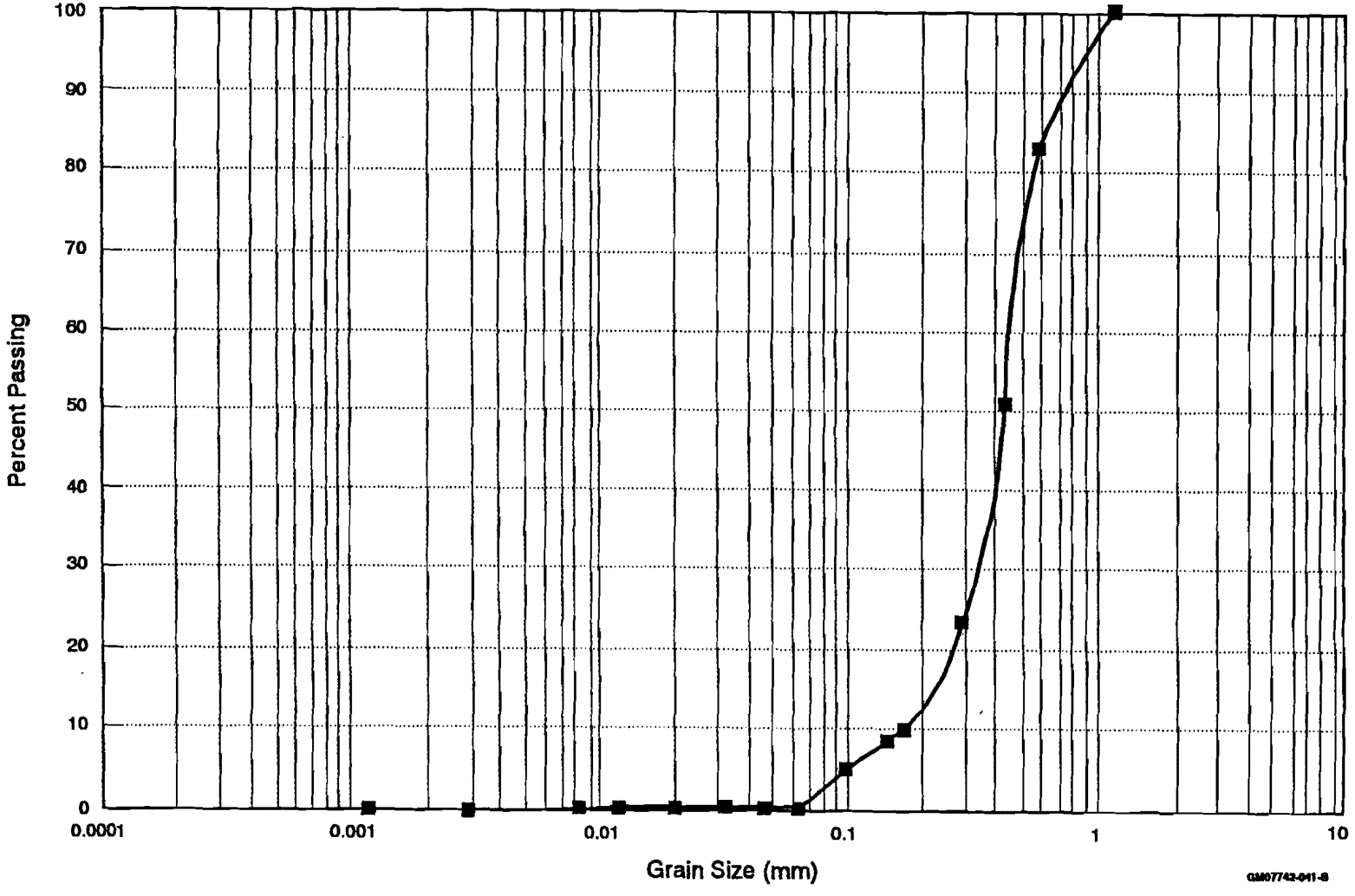


Figure 28. Grain size distribution curve (0.6 to 1.2 metres).

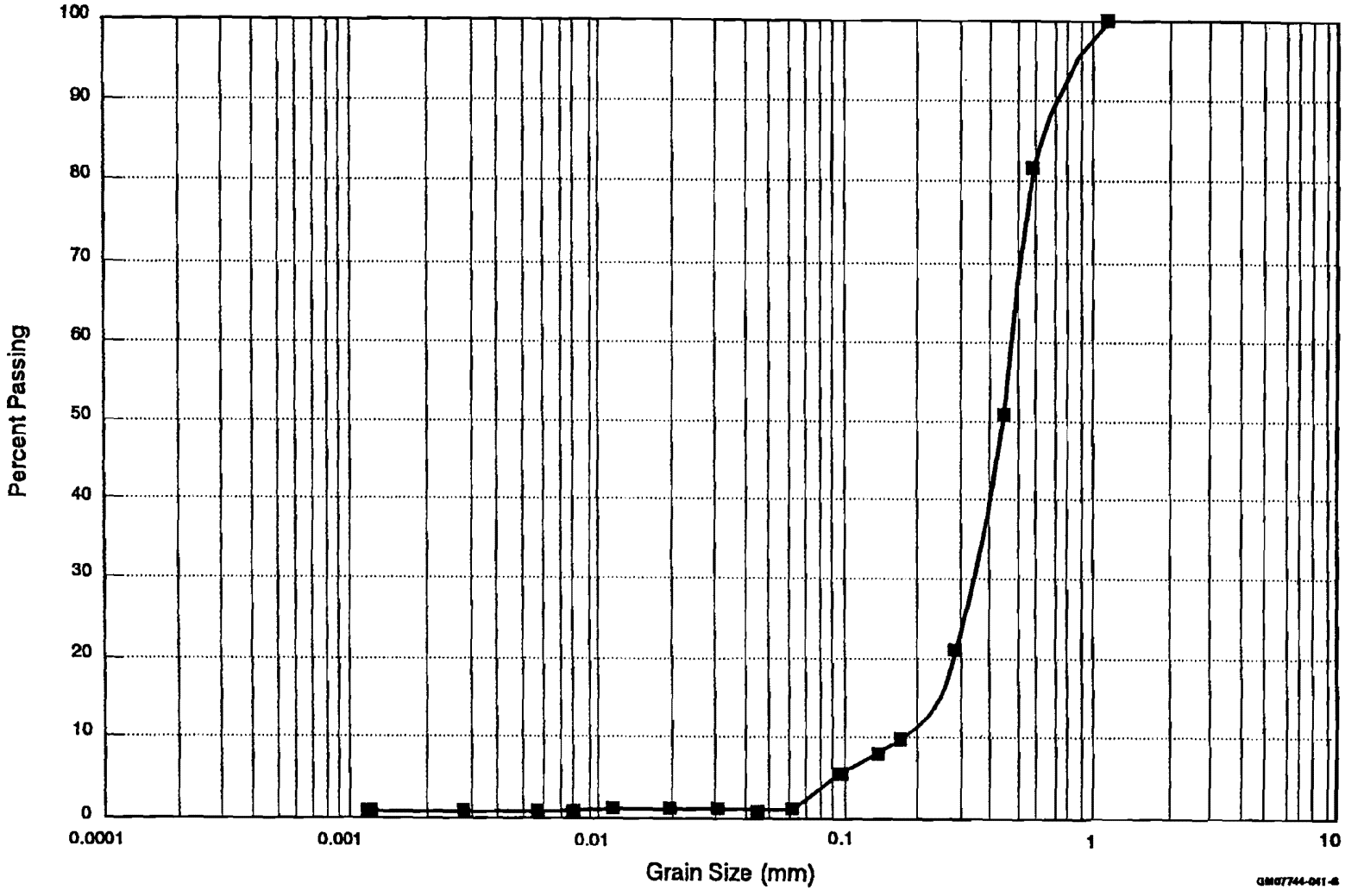


Figure 29. Grain size distribution curve (1.2 to 1.8 metres).

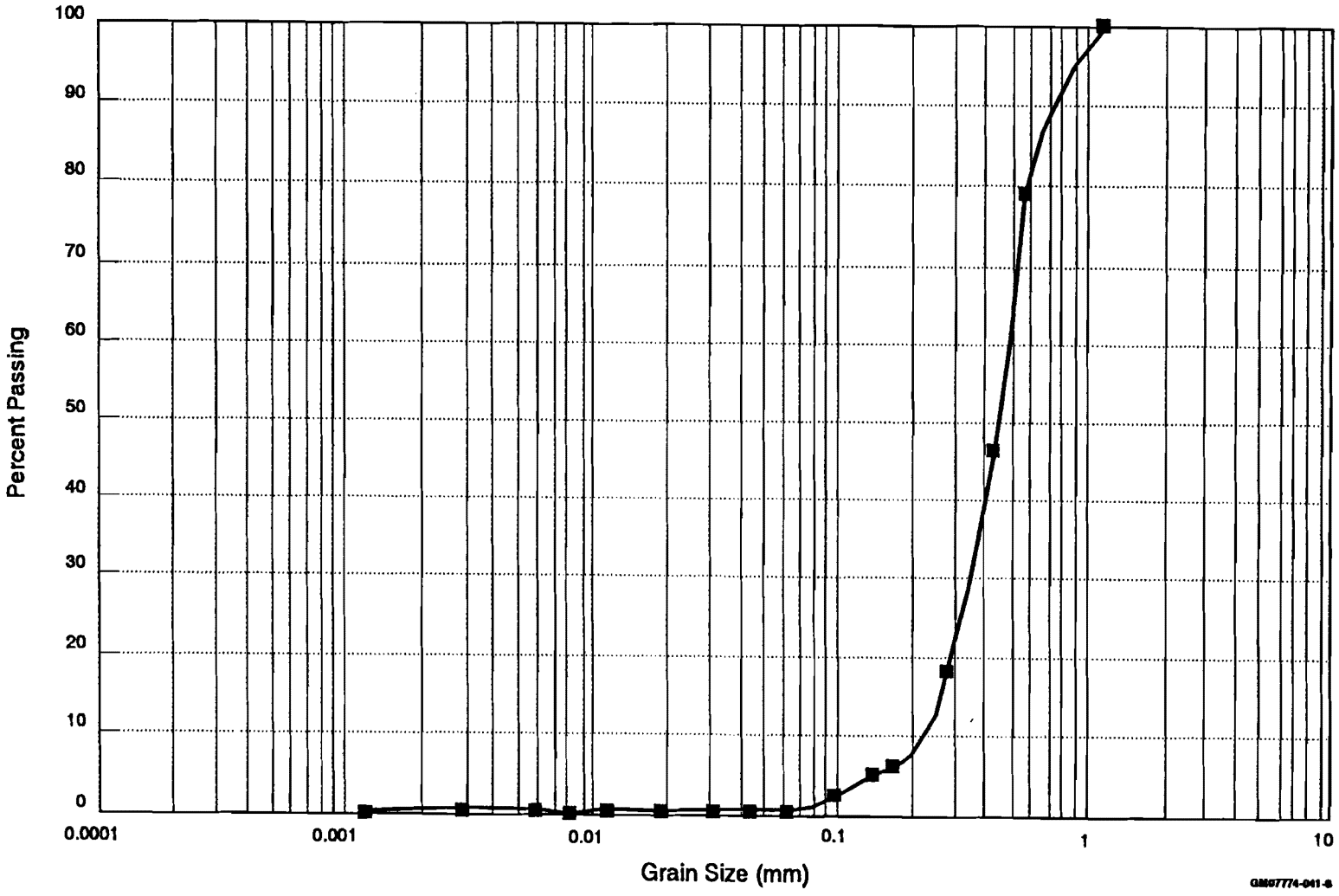


Figure 30. Grain size distribution curve (1.8 to 2.4 metres).

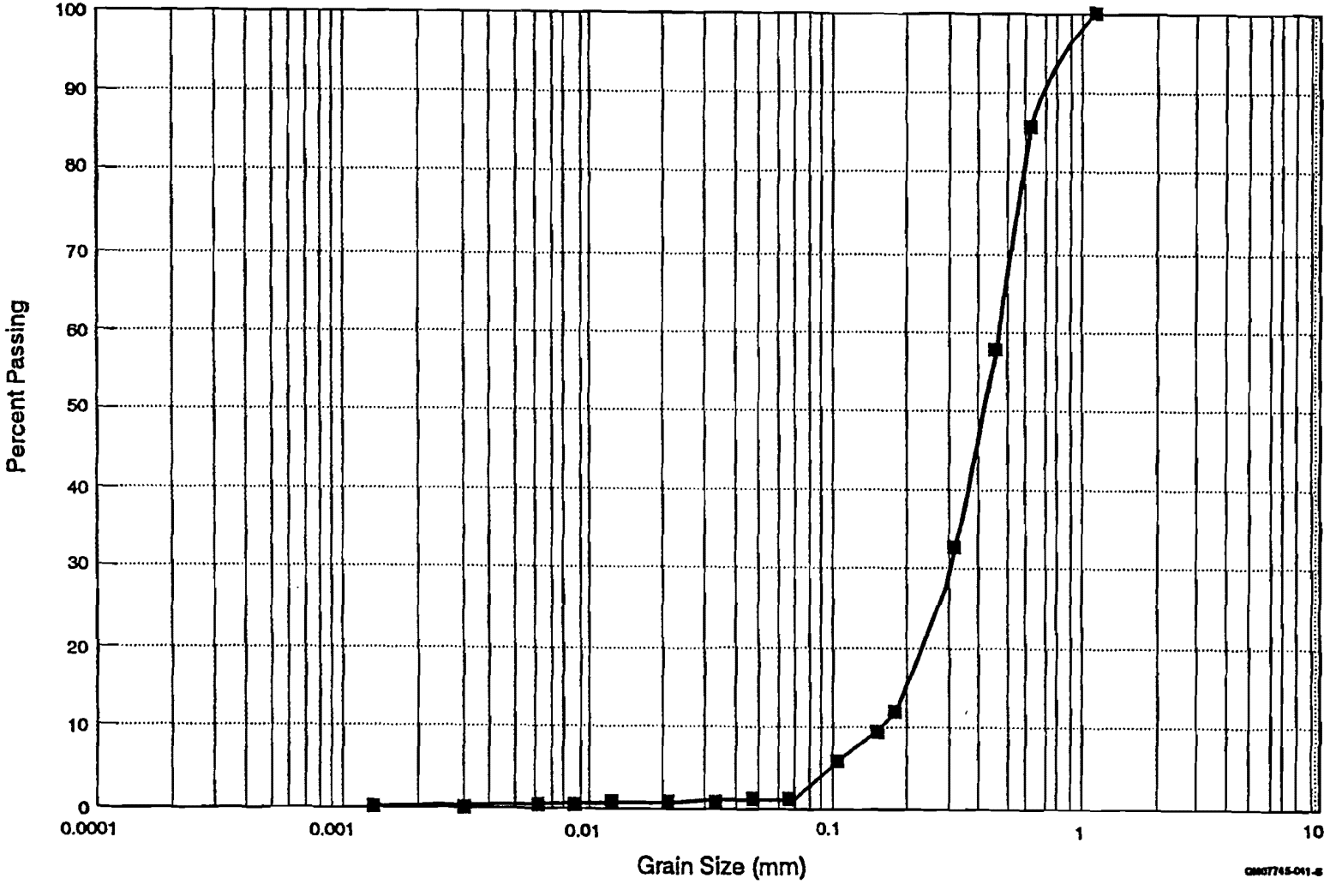


Figure 31. Grain size distribution curve (2.4 to 3.0 metres).

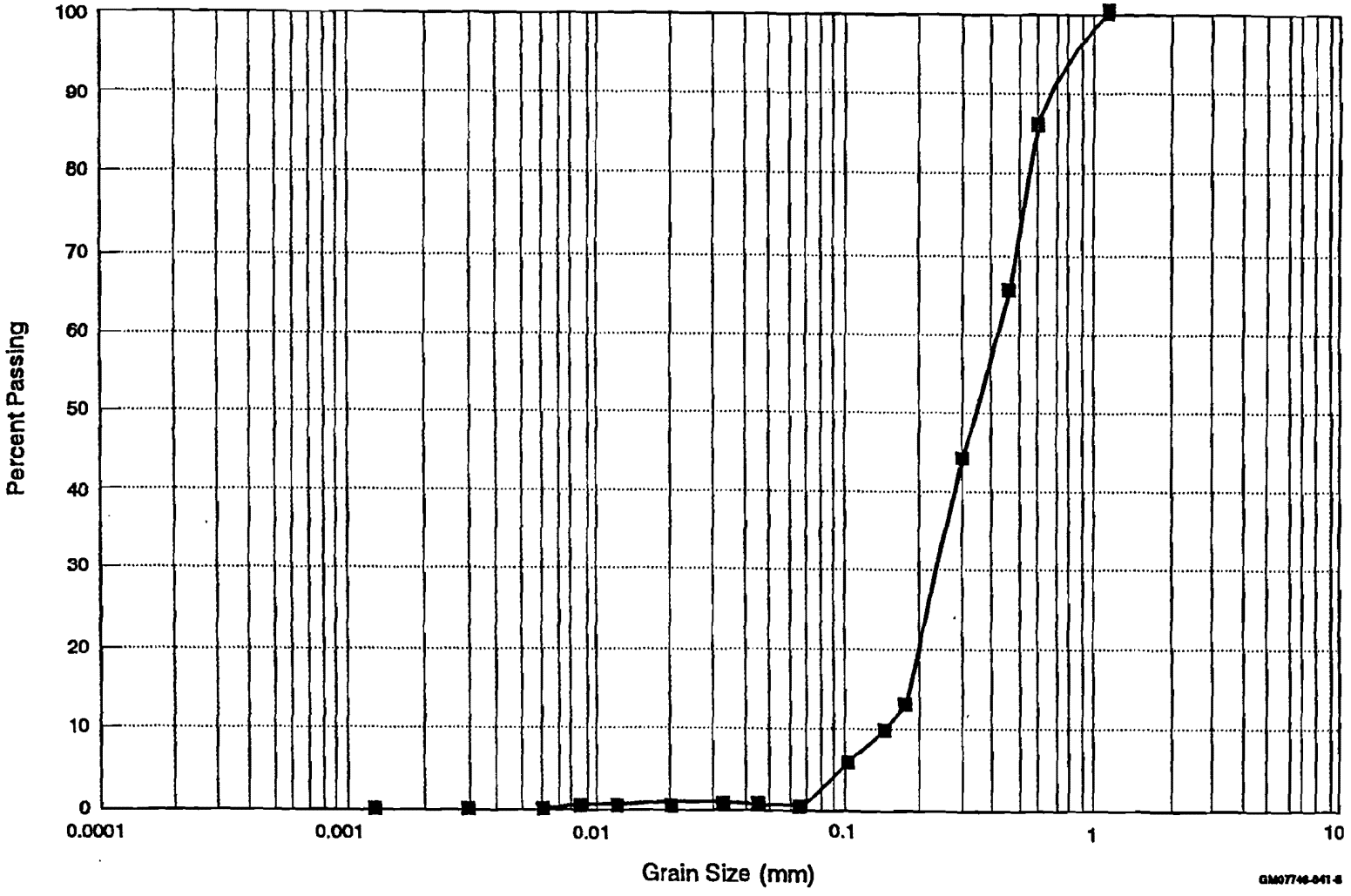


Figure 32. Grain size distribution curve (3.0 to 3.7 metres).

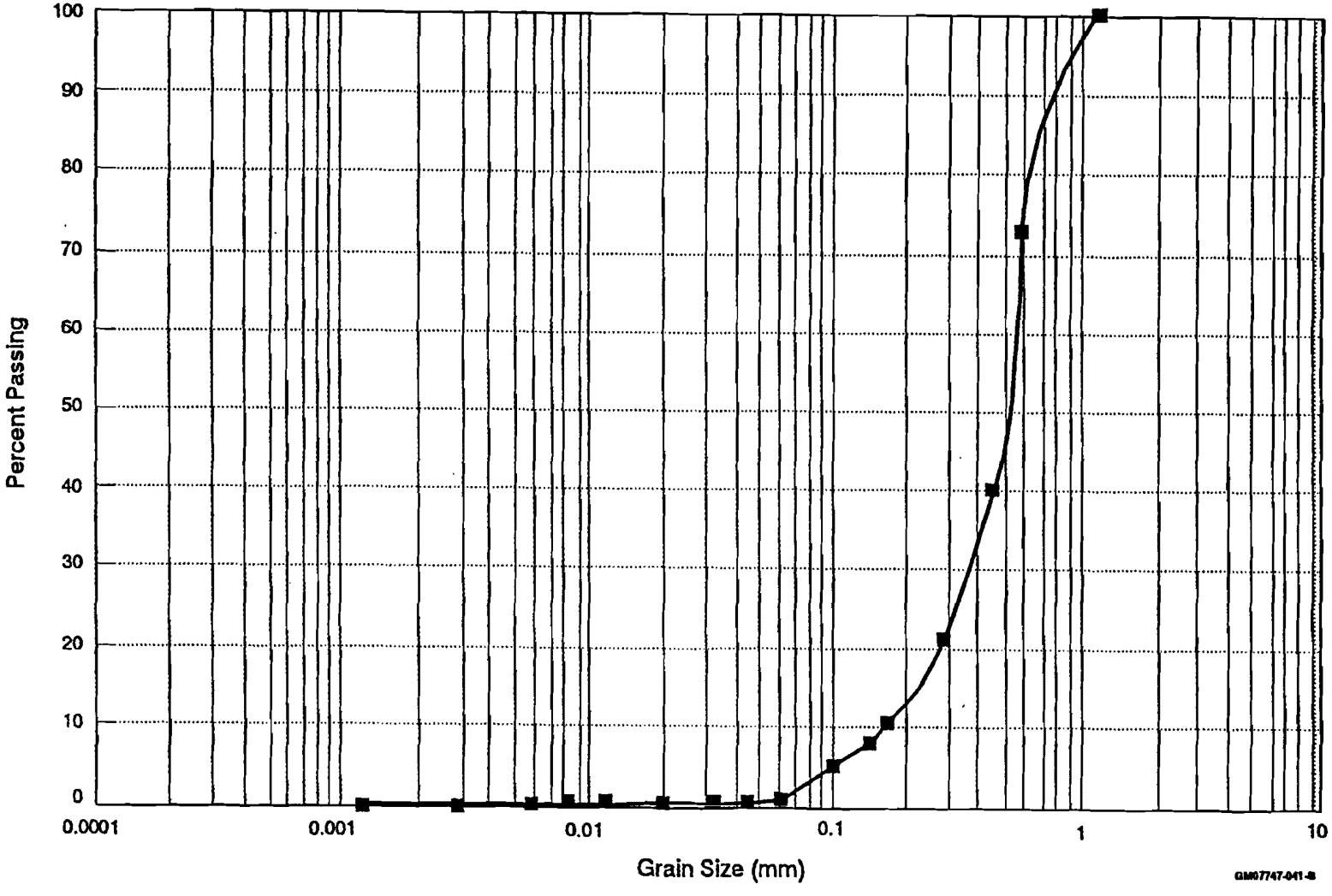


Figure 33. Grain size distribution curve (3.7 to 4.3 metres).

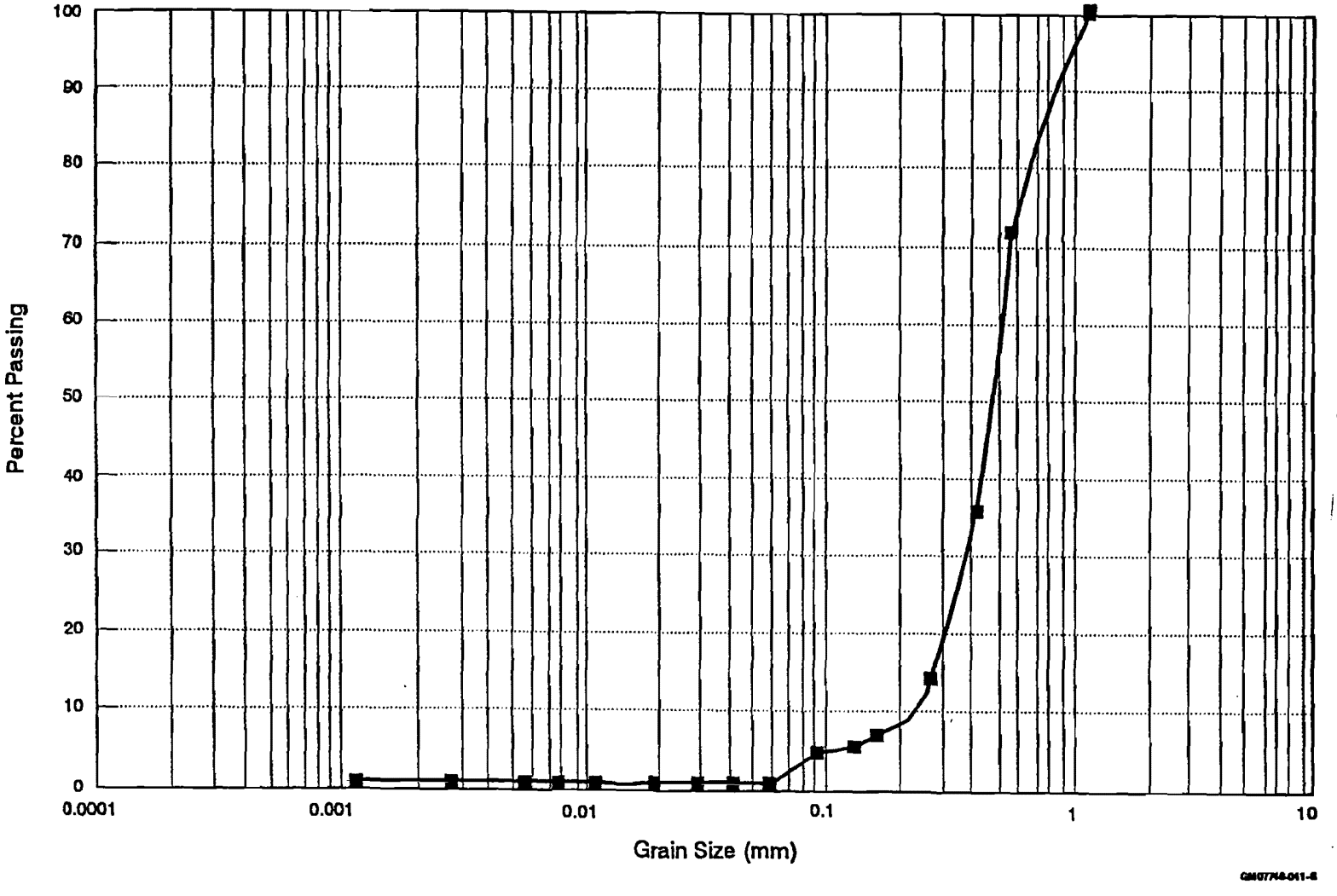


Figure 34. Grain size distribution curve (4.3 to 4.9 metres).

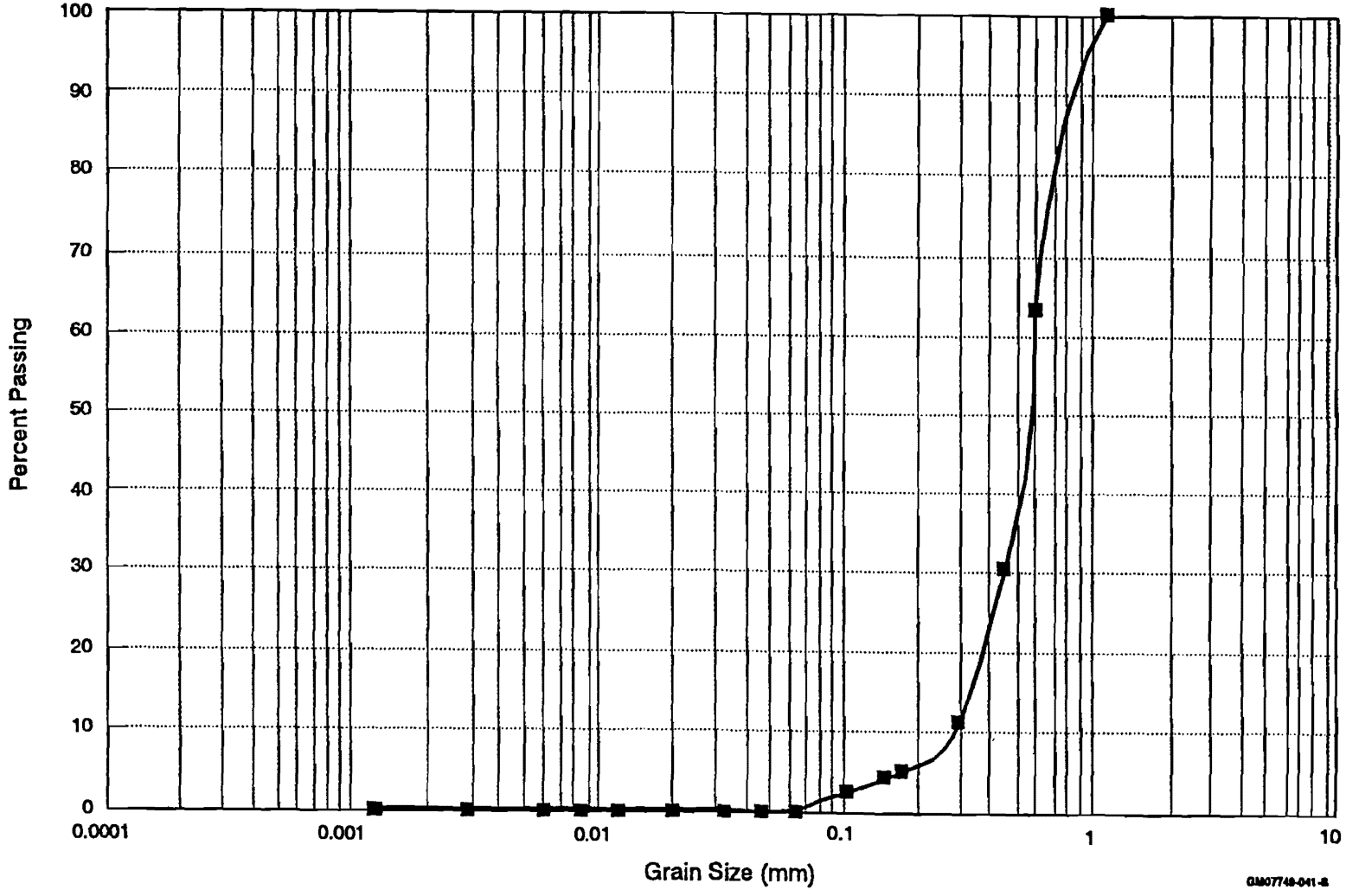


Figure 35. Grain size distribution curve (4.9 to 5.5 metres).

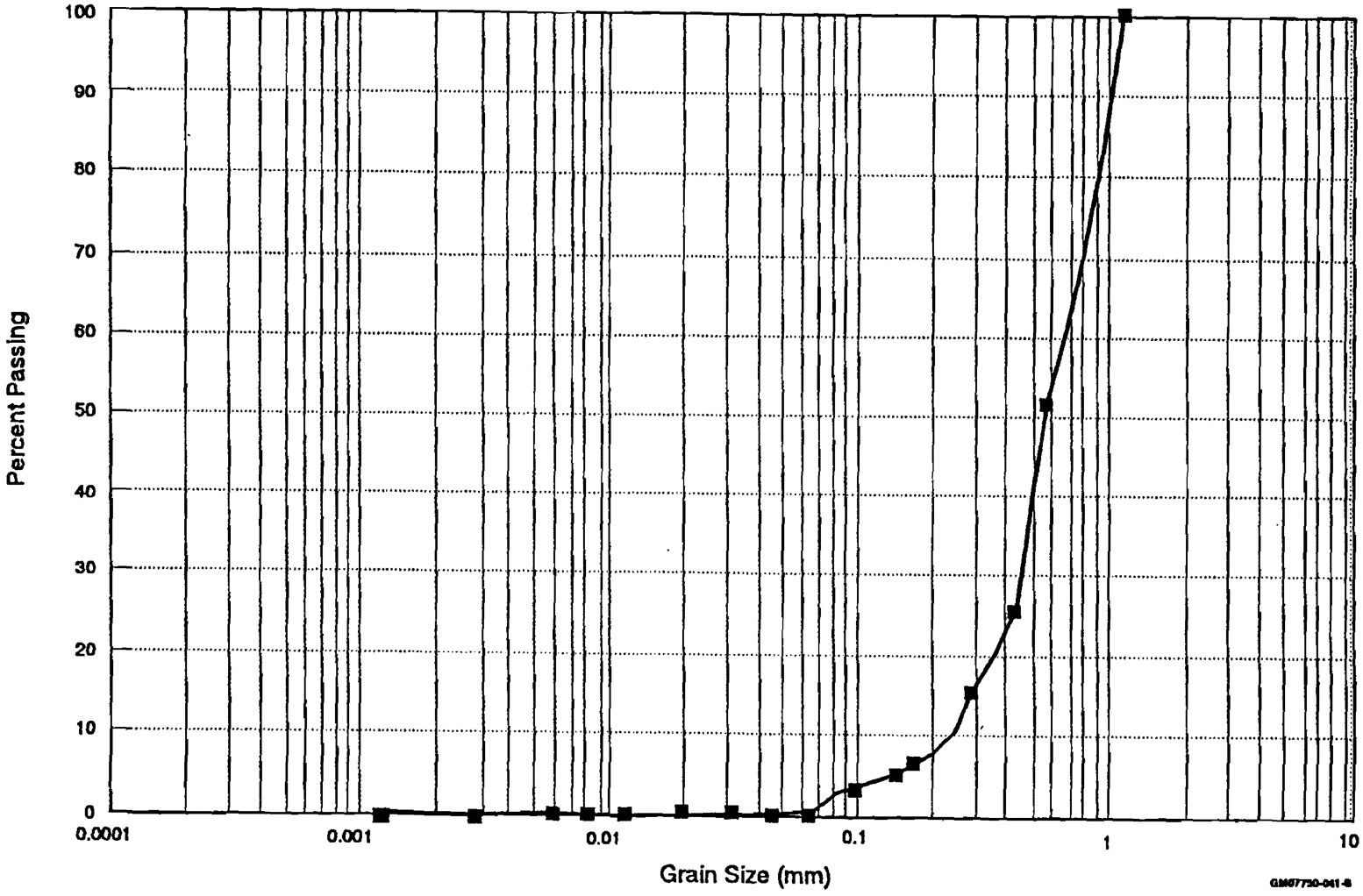


Figure 36. Grain size distribution curve (5.5 to 6.1 metres).

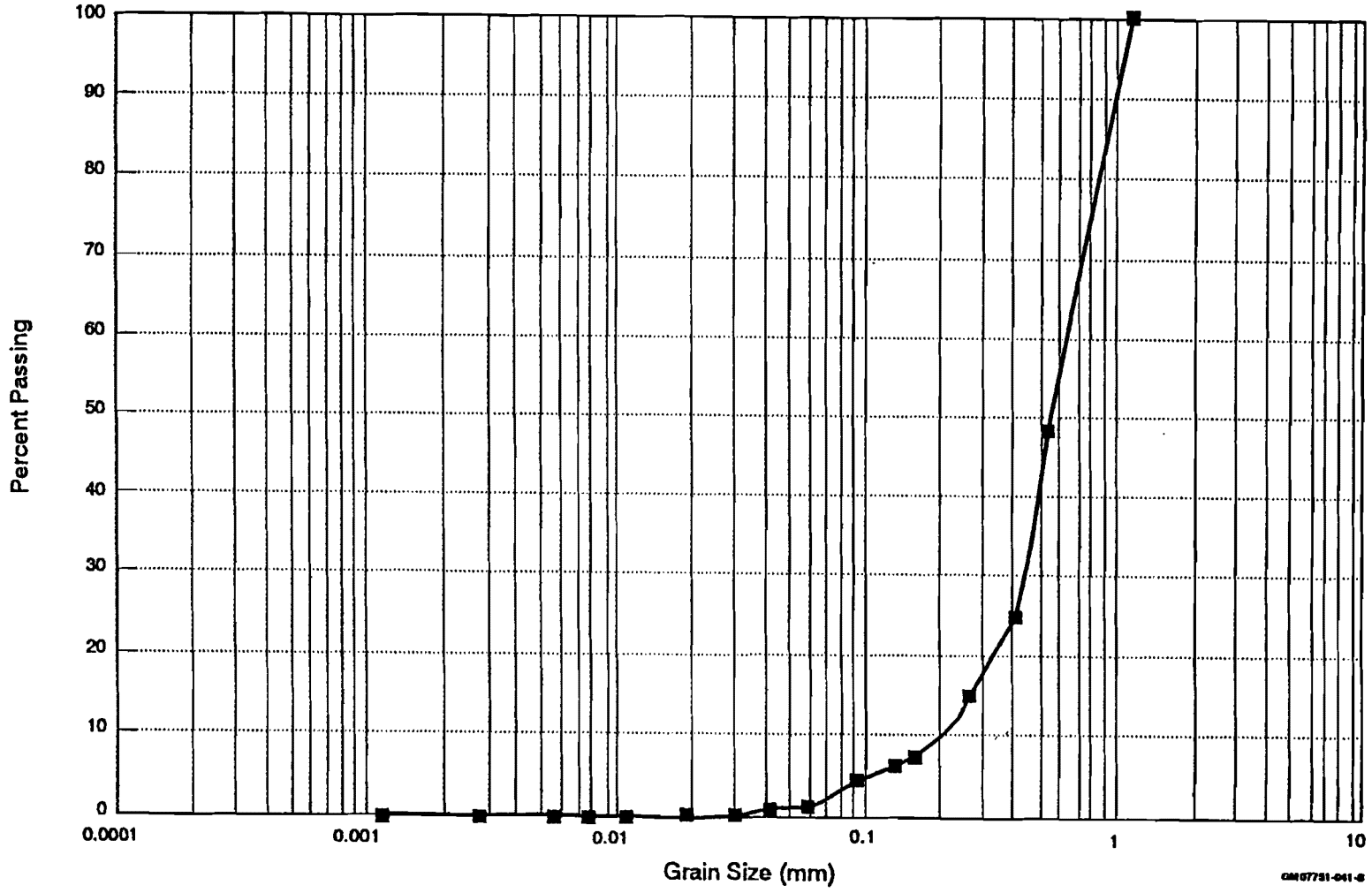


Figure 37. Grain size distribution curve (6.1 to 6.7 metres).

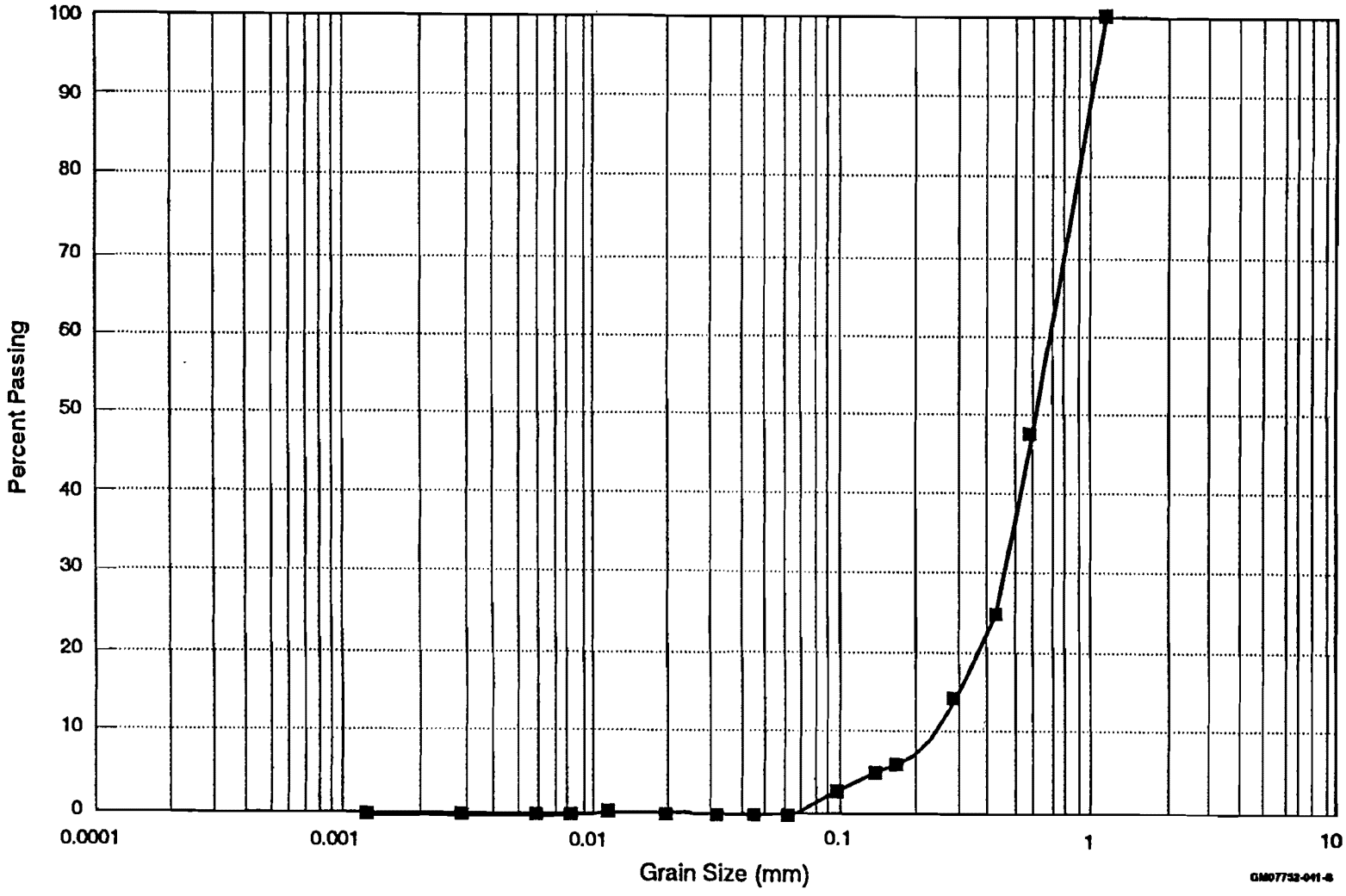


Figure 38. Grain size distribution curve (6.7 to 7.3 metres).

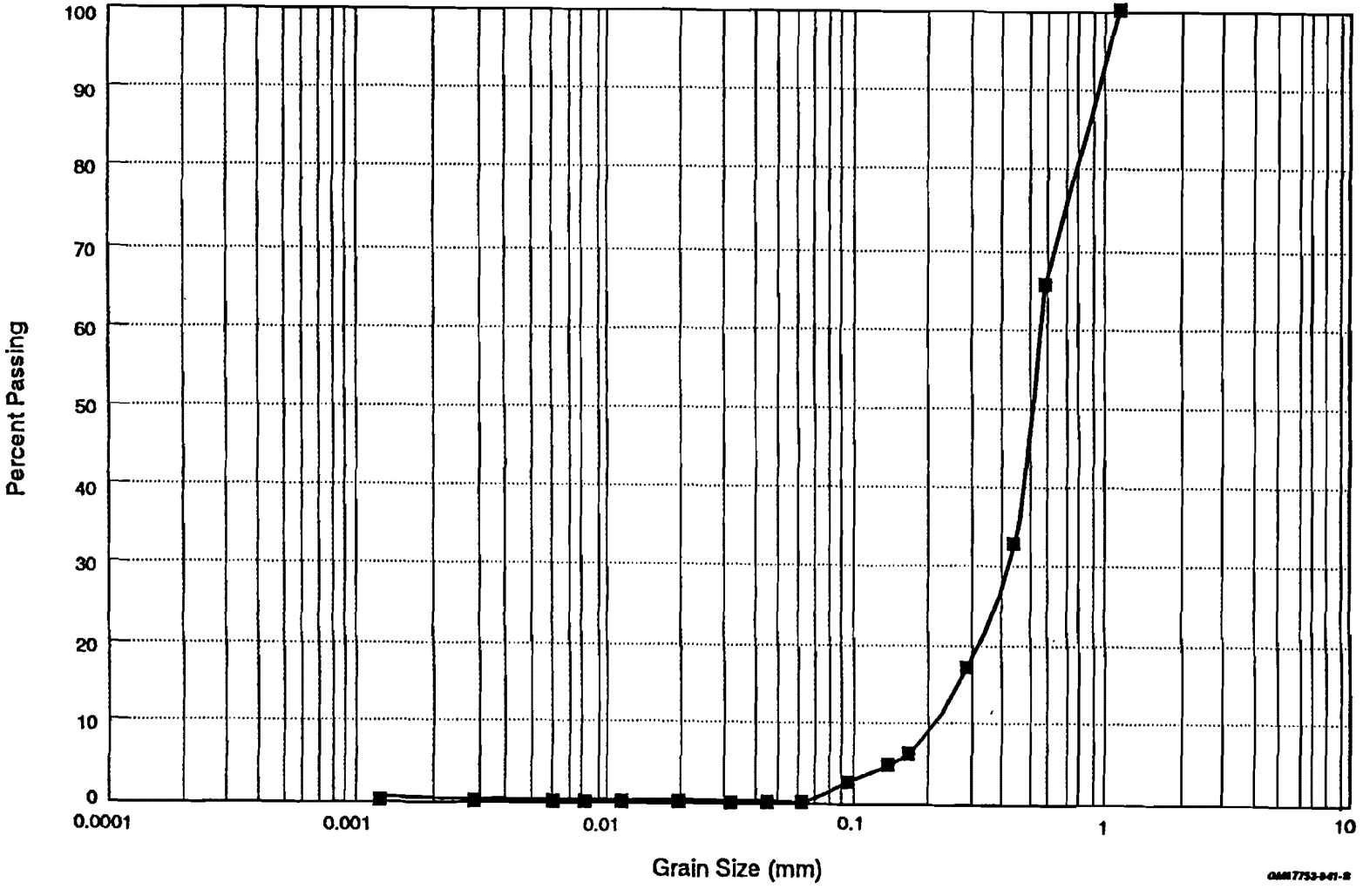


Figure 39. Grain size distribution curve (7.3 to 7.9 metres).

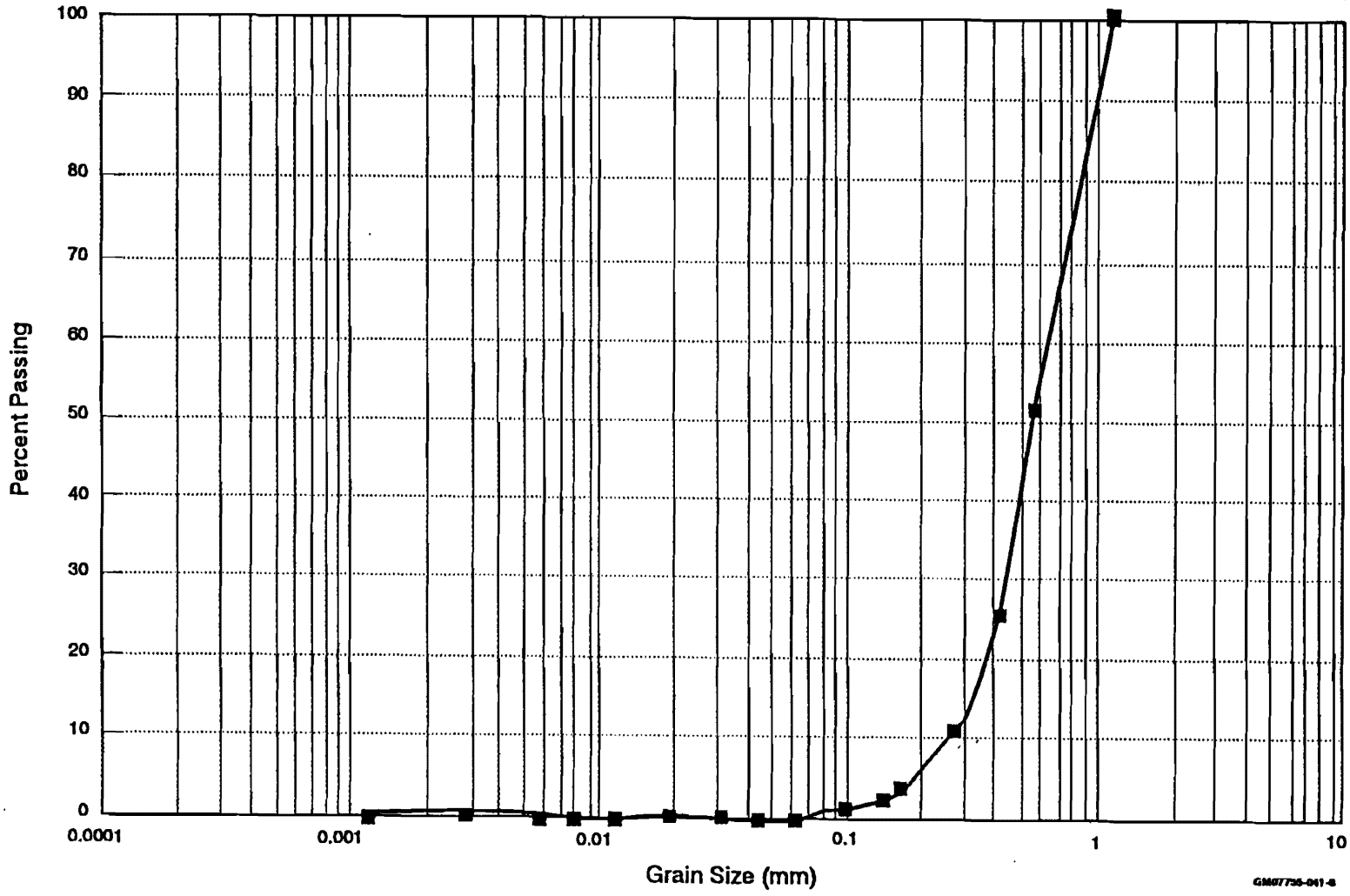


Figure 40. Grain size distribution curve (7.9 to 8.5 metres).

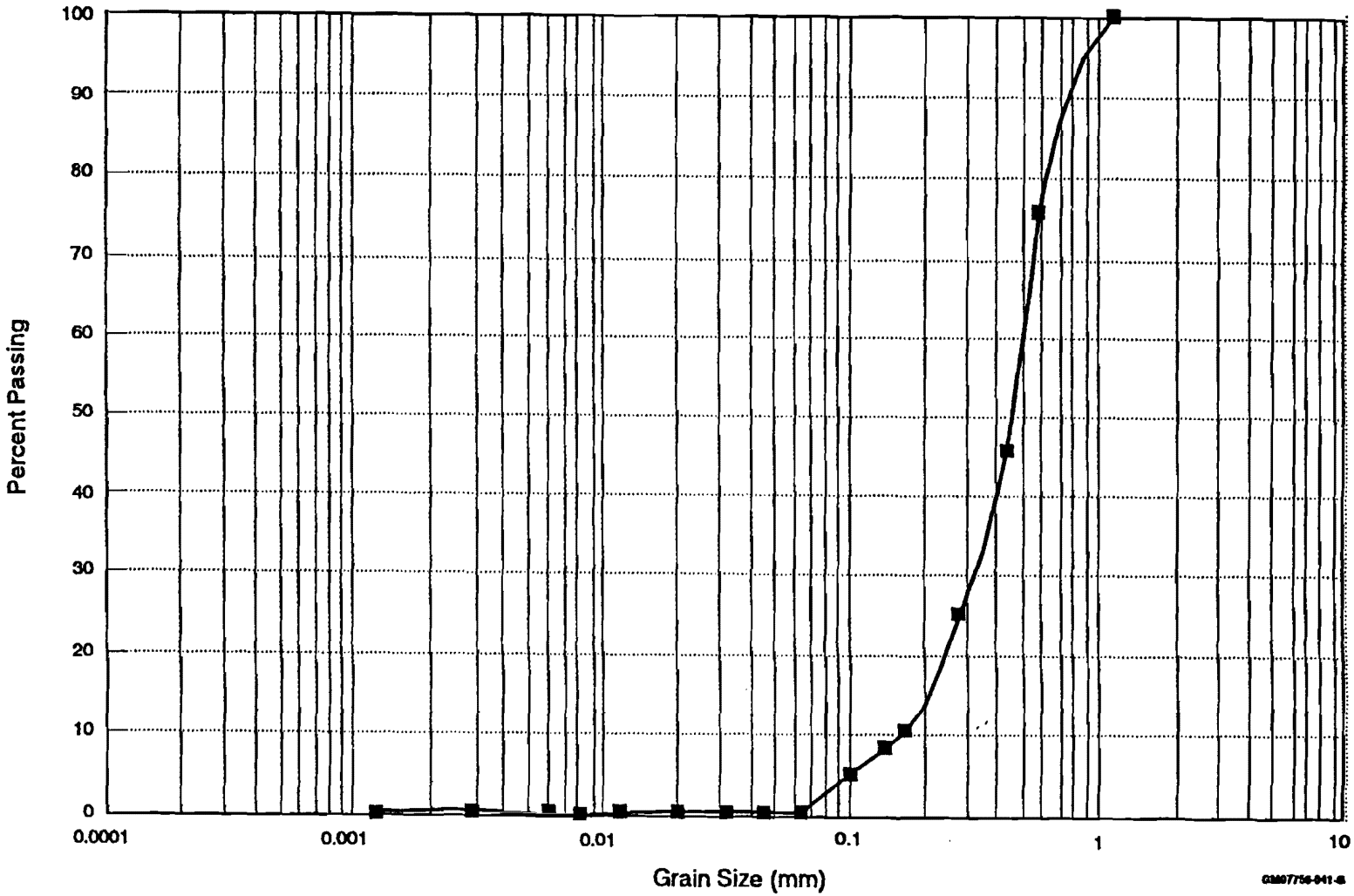


Figure 41. Grain size distribution curve (8.5 to 9.1 metres).

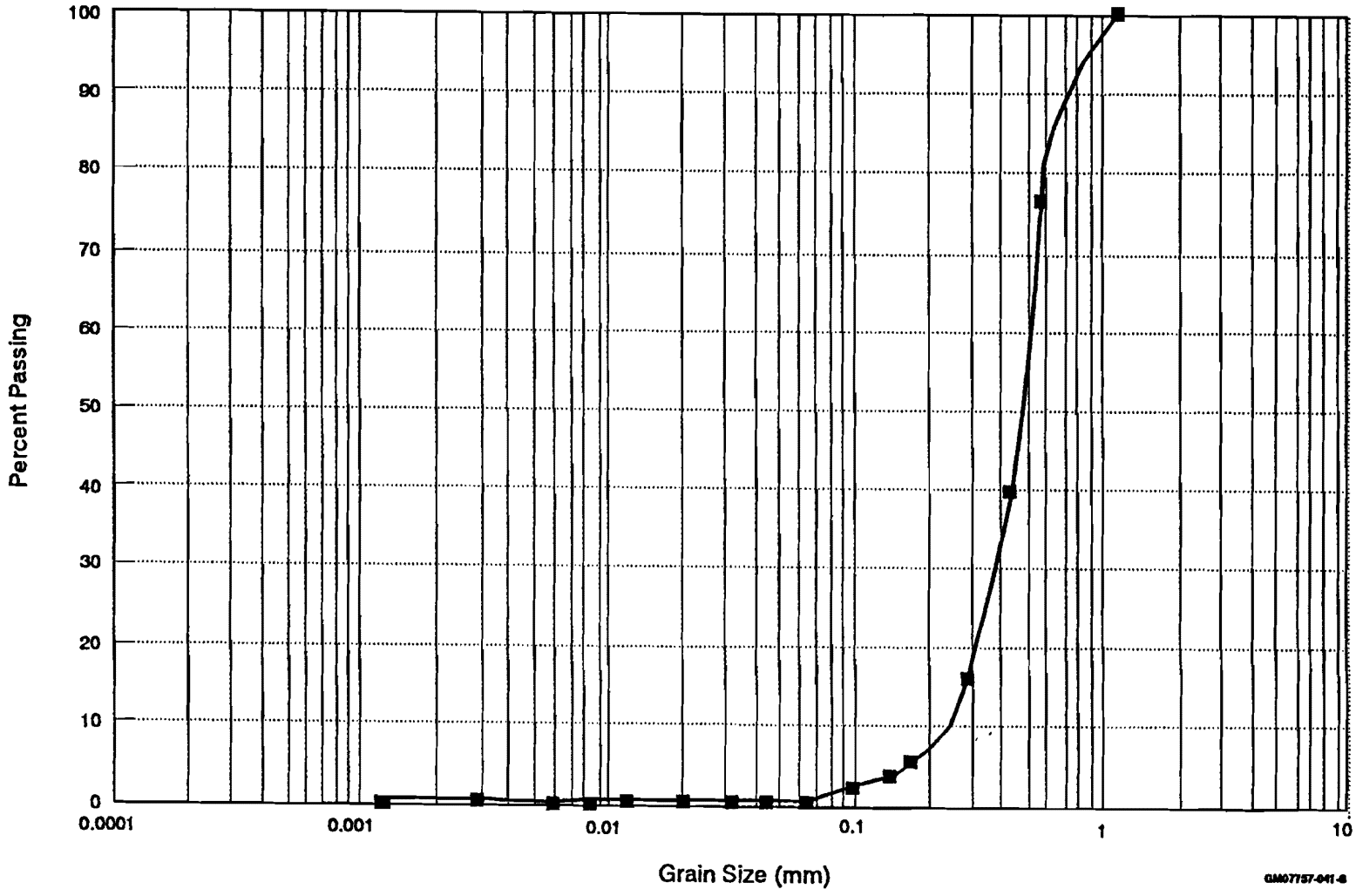


Figure 42. Grain size distribution curve (9.1 to 9.8 metres).

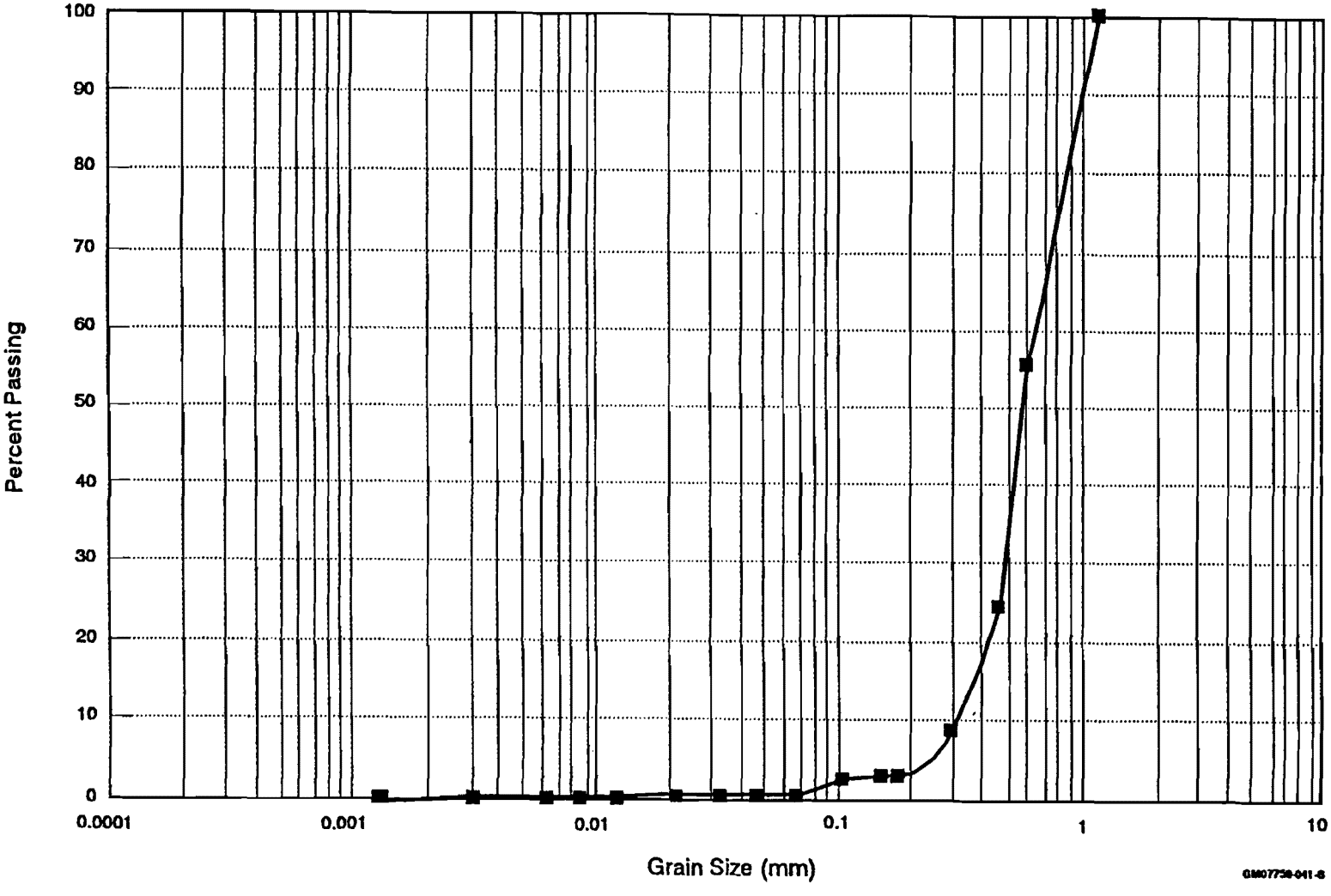


Figure 43. Grain size distribution curve (9.8 to 10.4 metres).

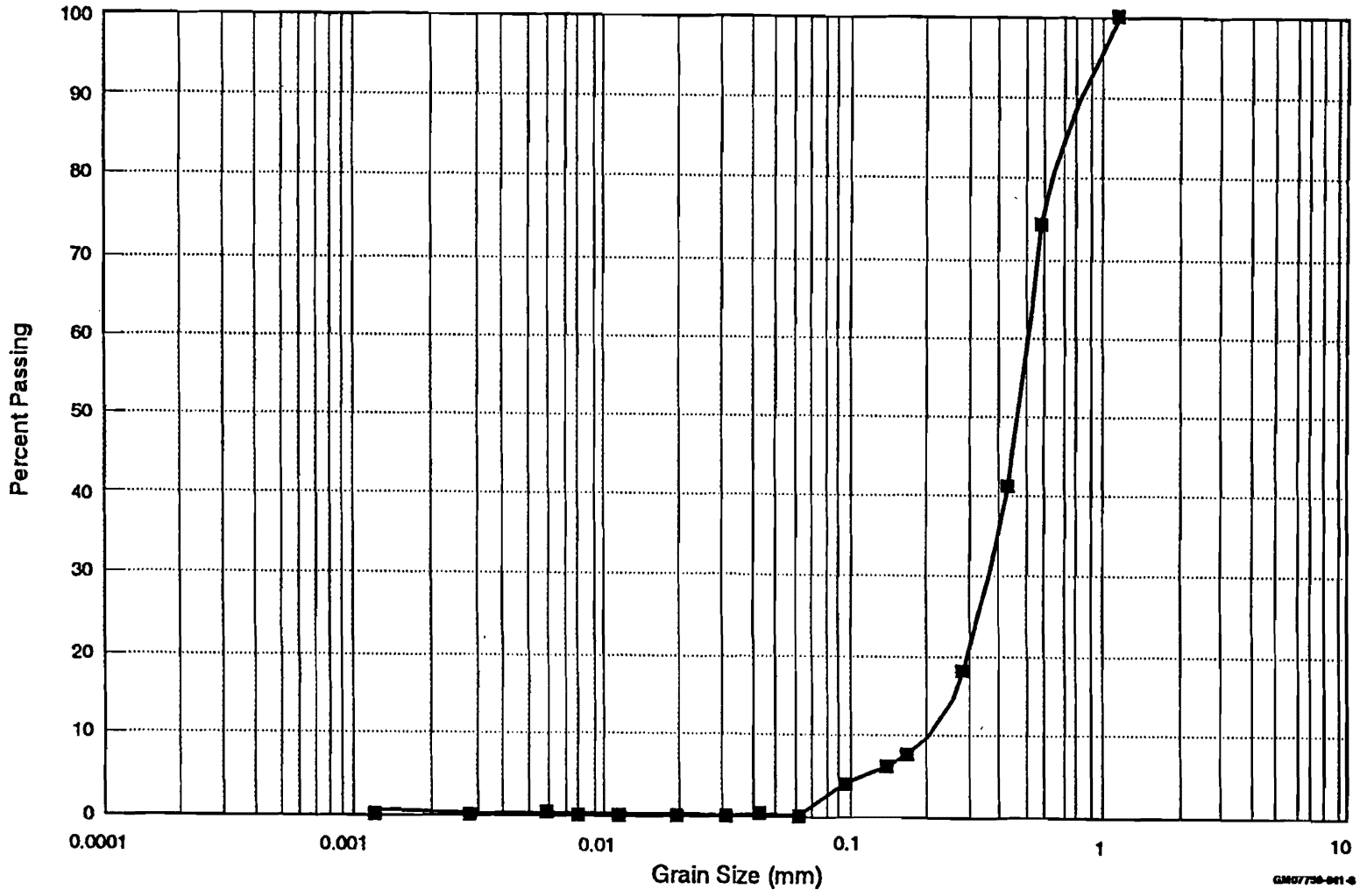


Figure 44. Grain size distribution curve (10.4 to 11.0 metres).

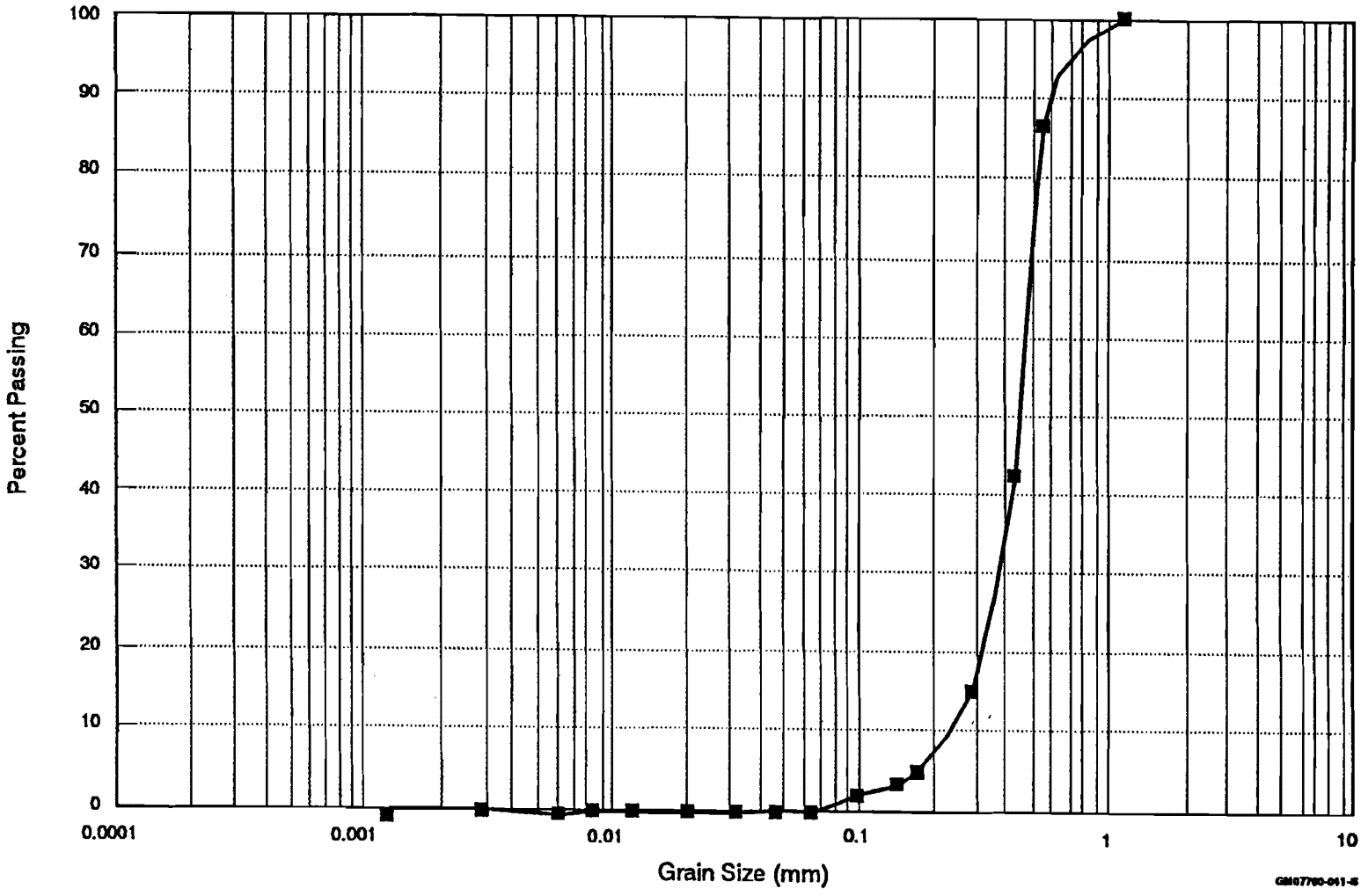


Figure 45. Grain size distribution curve (11.0 to 11.6 metres).

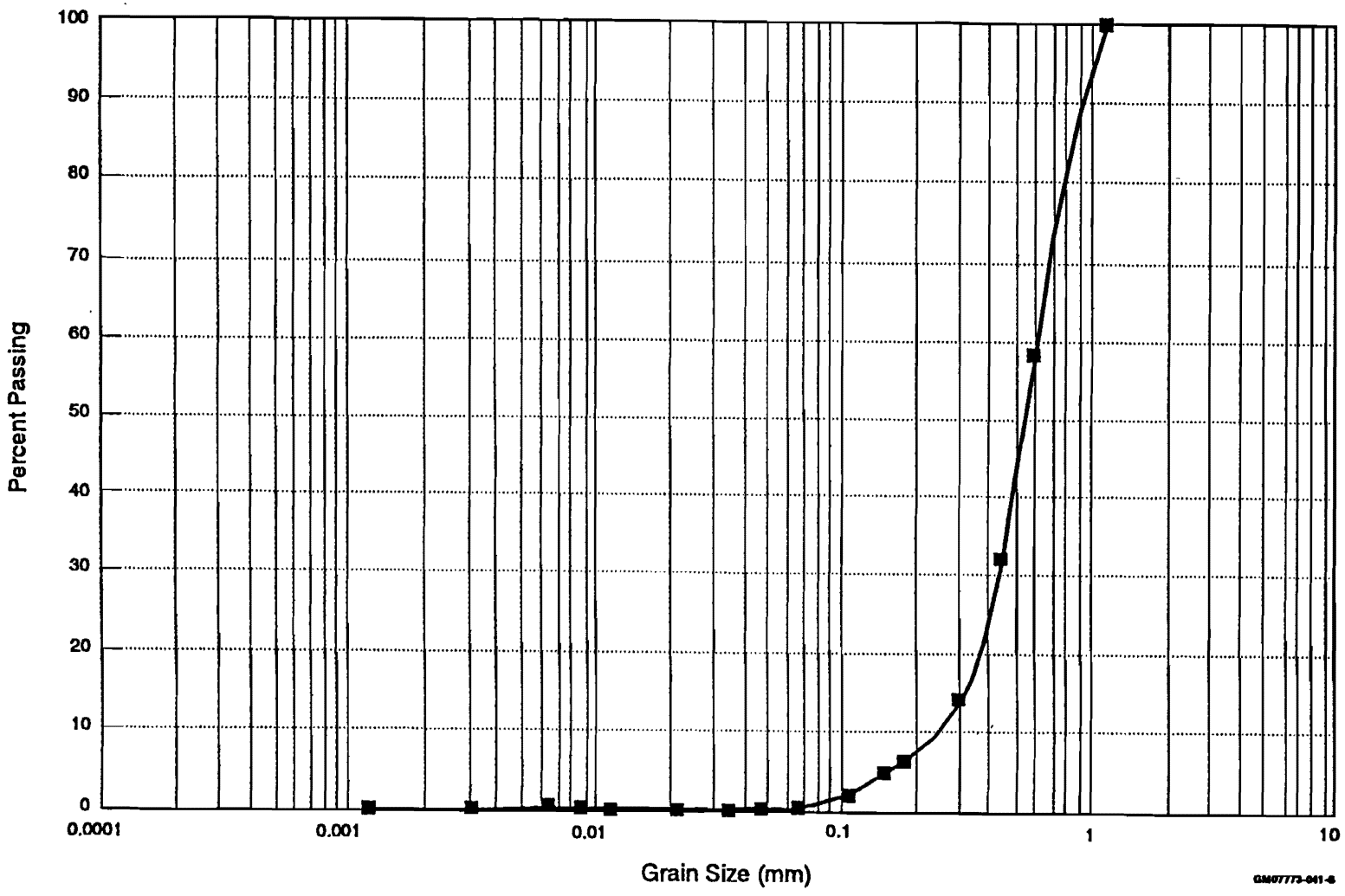


Figure 46. Grain size distribution curve (11.6 to 12.2 metres).

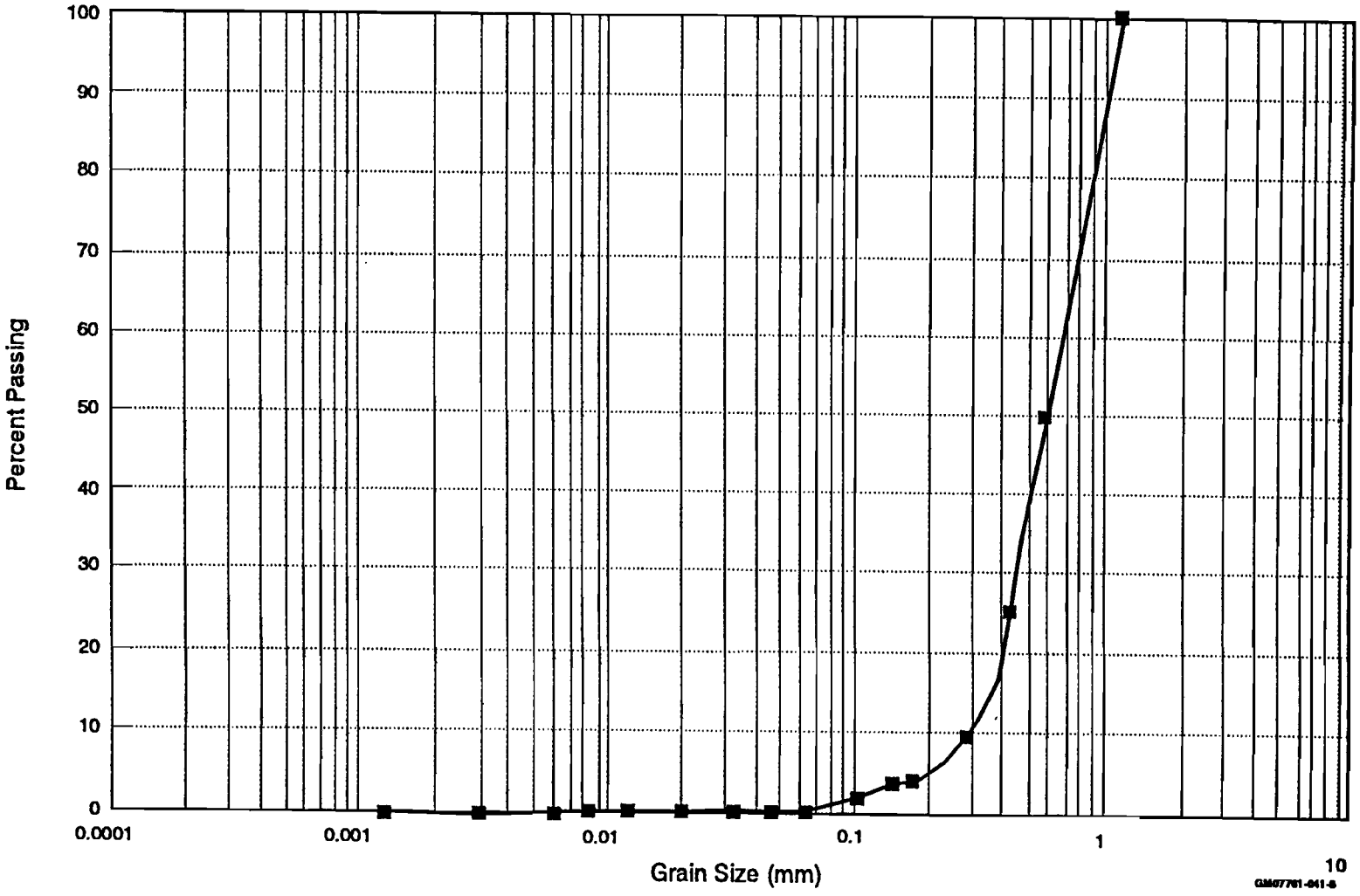


Figure 47. Grain size distribution curve (12.2 to 12.8 metres).

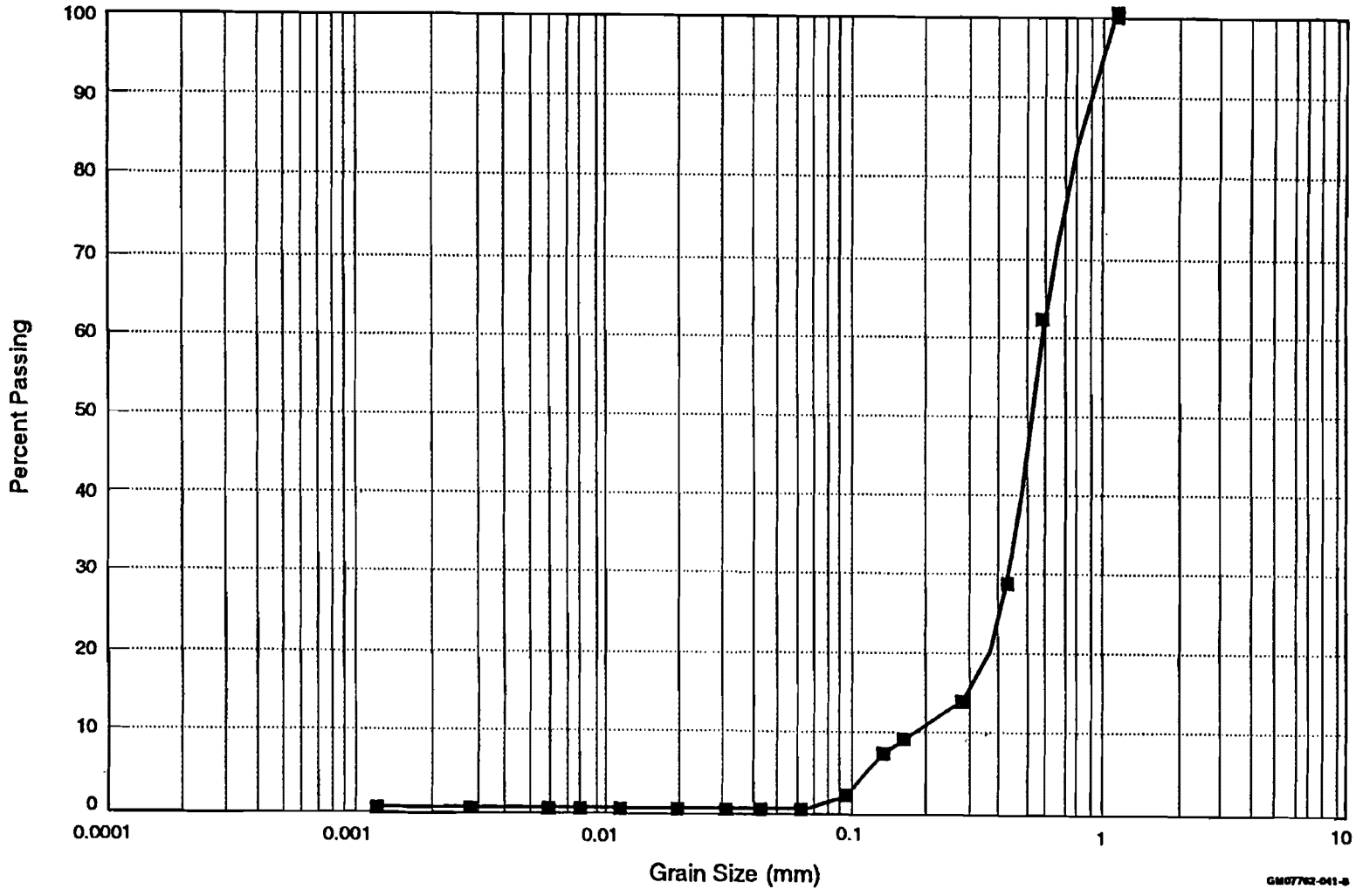


Figure 48. Grain size distribution curve (12.8 to 13.4 metres).

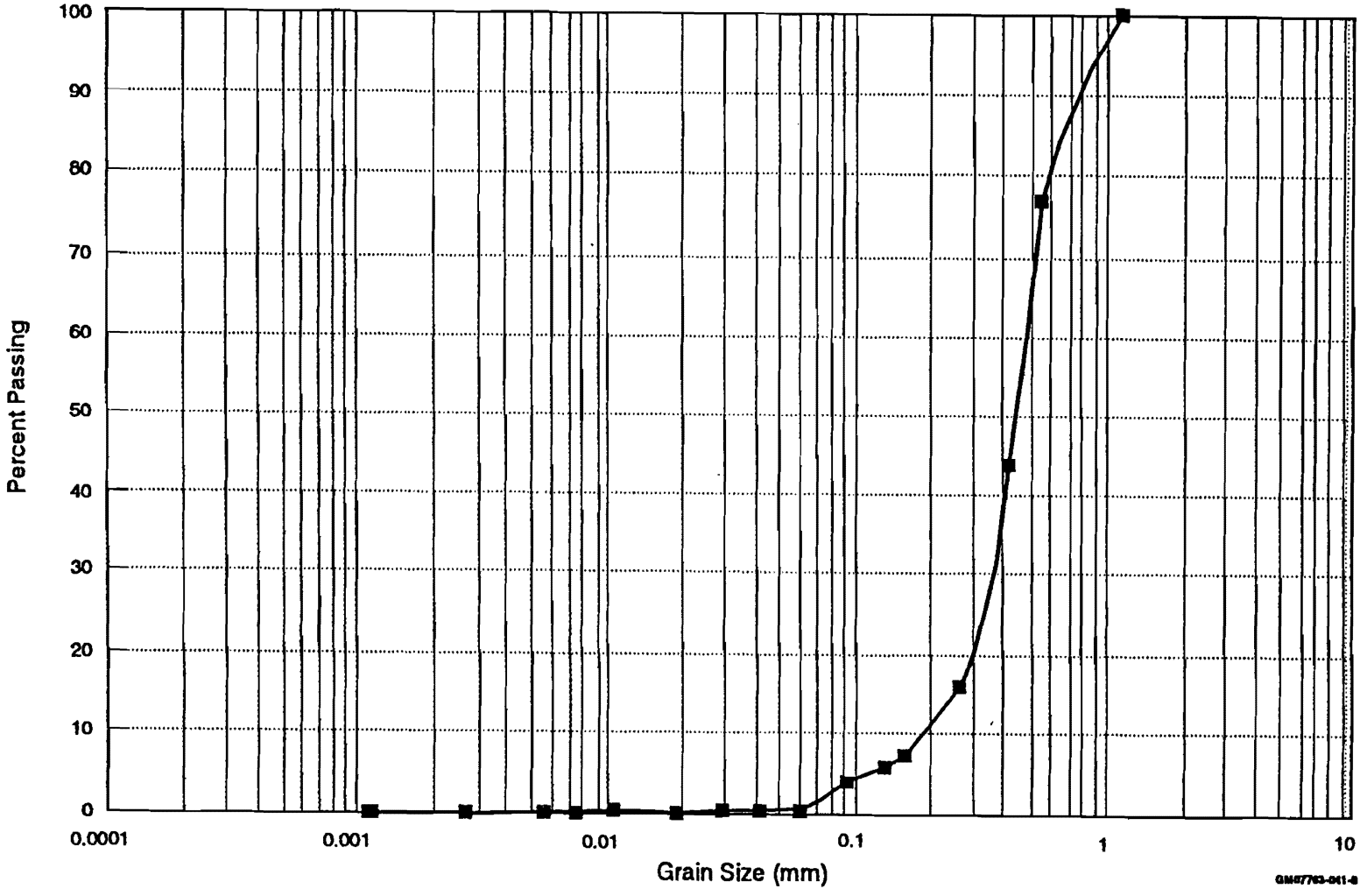


Figure 49. Grain size distribution curve (13.4 to 14.0 metres).

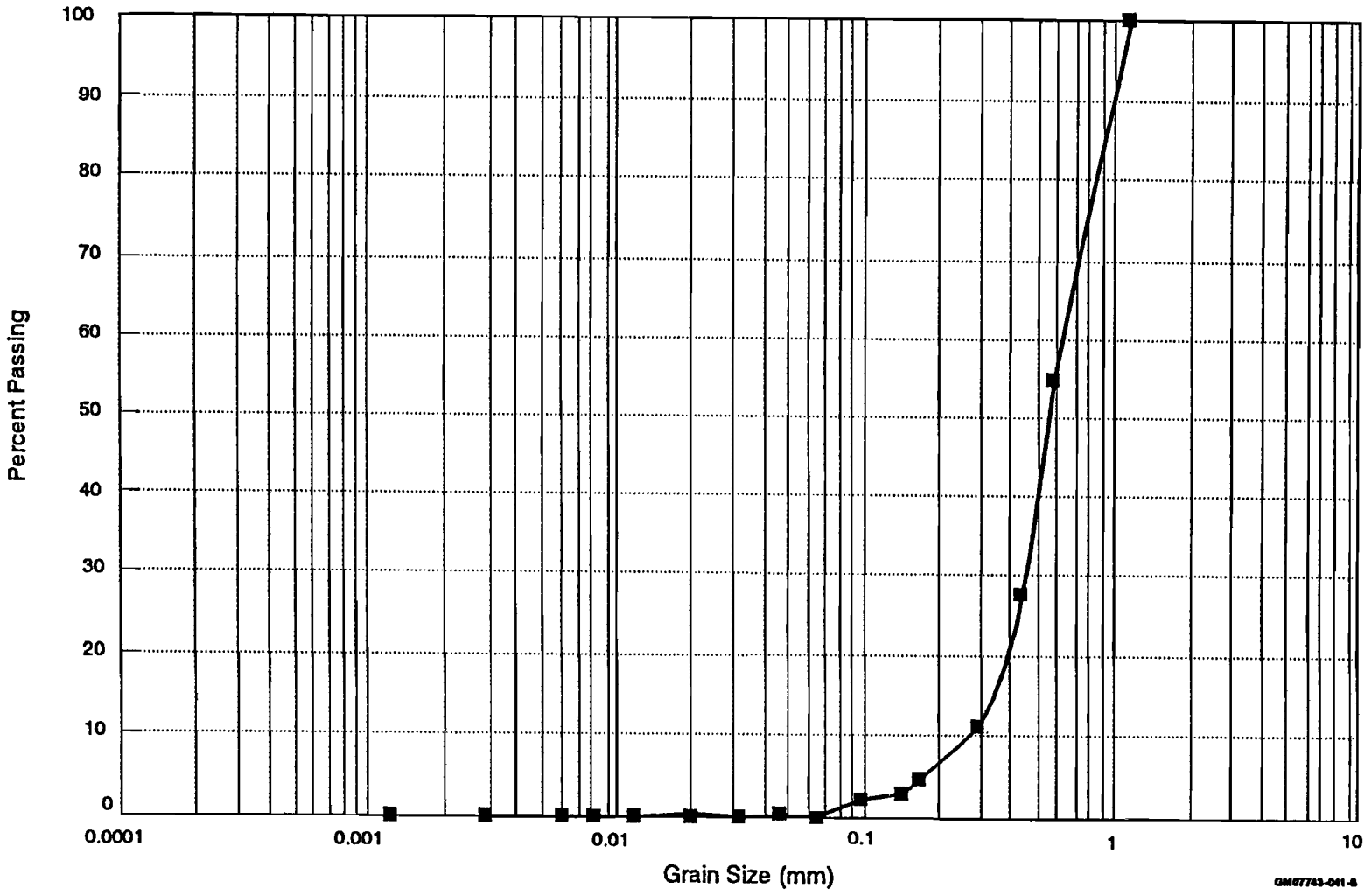


Figure 50. Grain size distribution curve (14.0 to 14.6 metres).

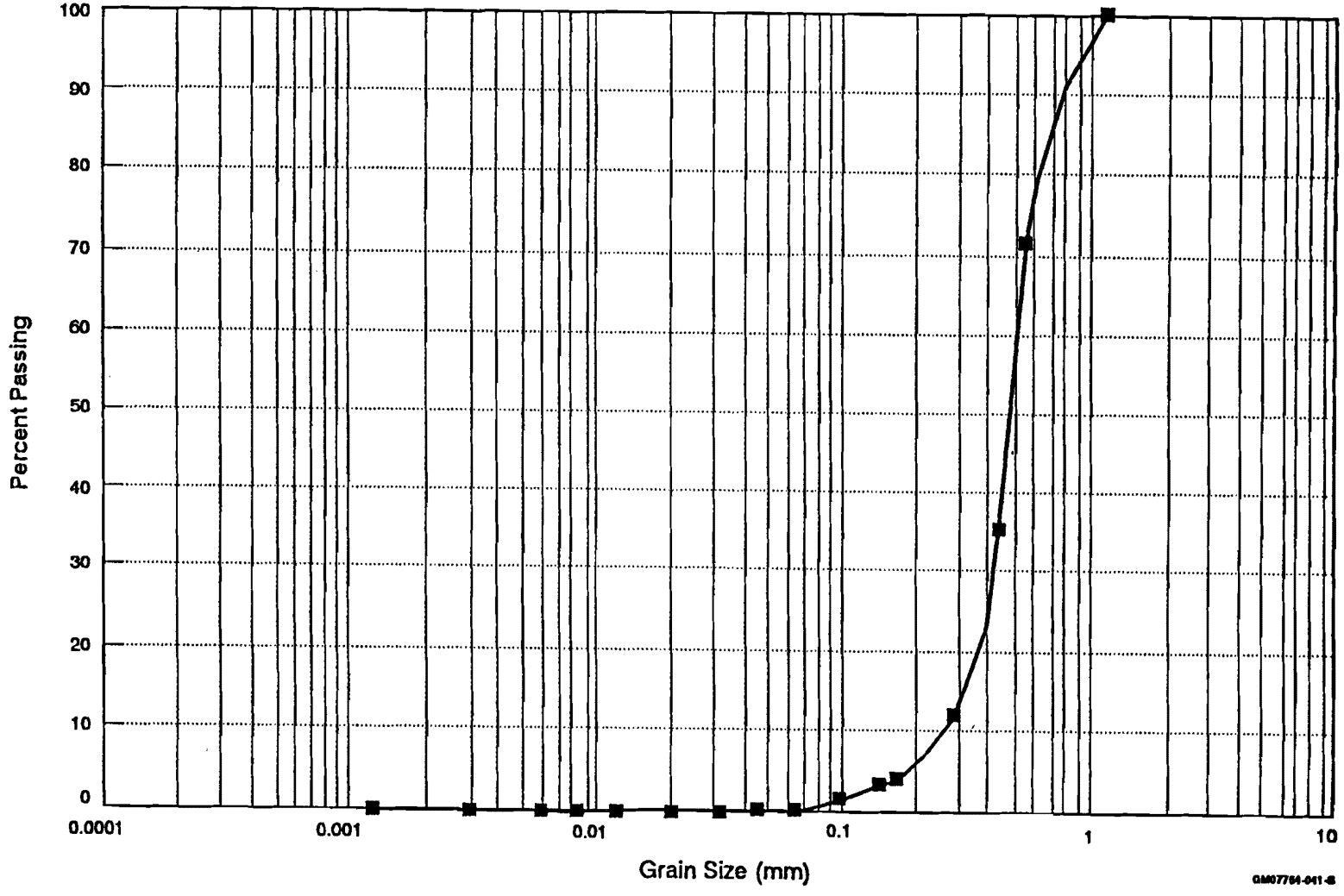


Figure 51. Grain size distribution curve (14.6 to 15.2 metres).

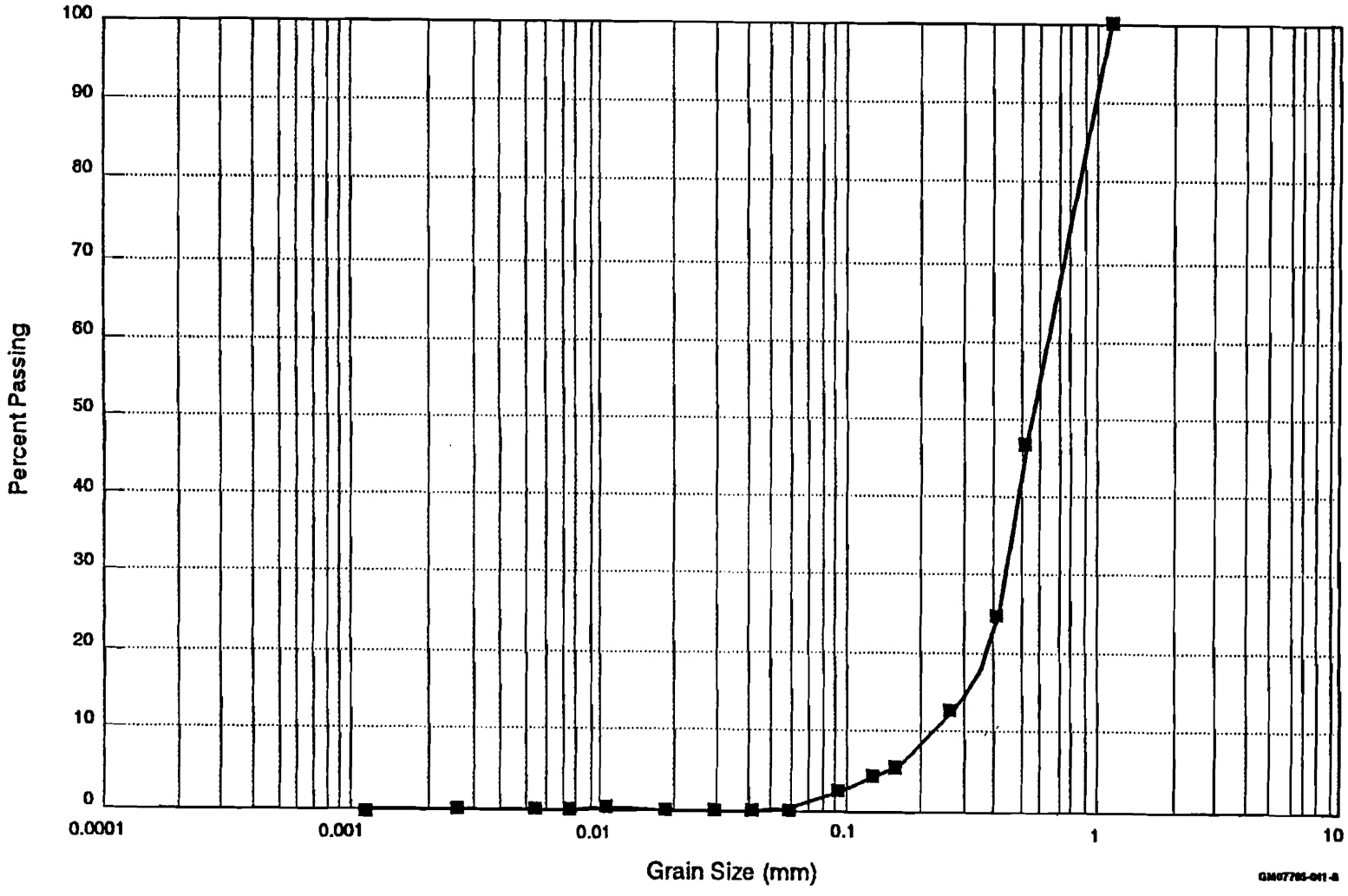


Figure 52. Grain size distribution curve (15.2 to 15.9 metres).

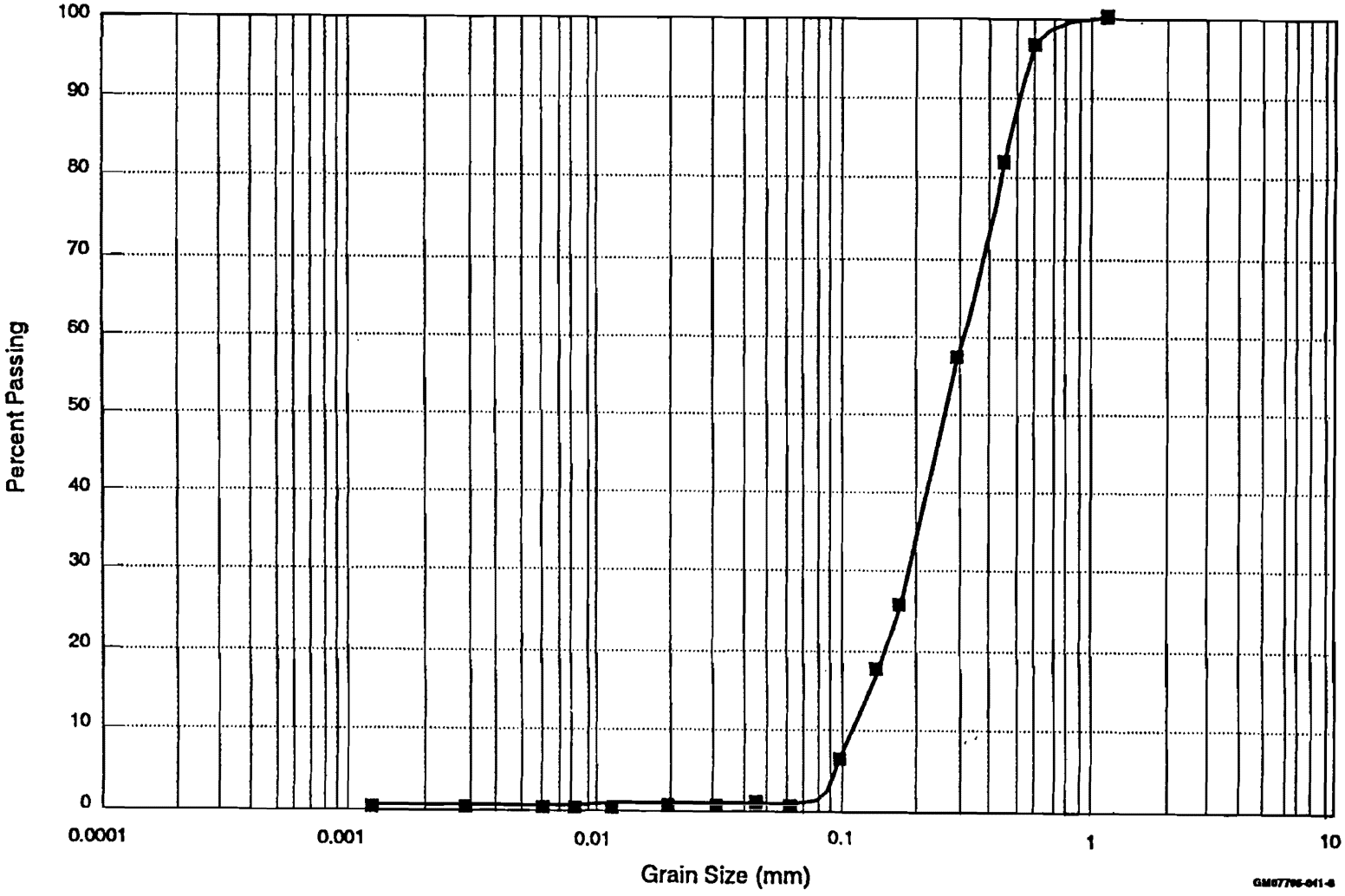


Figure 53. Grain size distribution curve (15.9 to 16.5 metres).

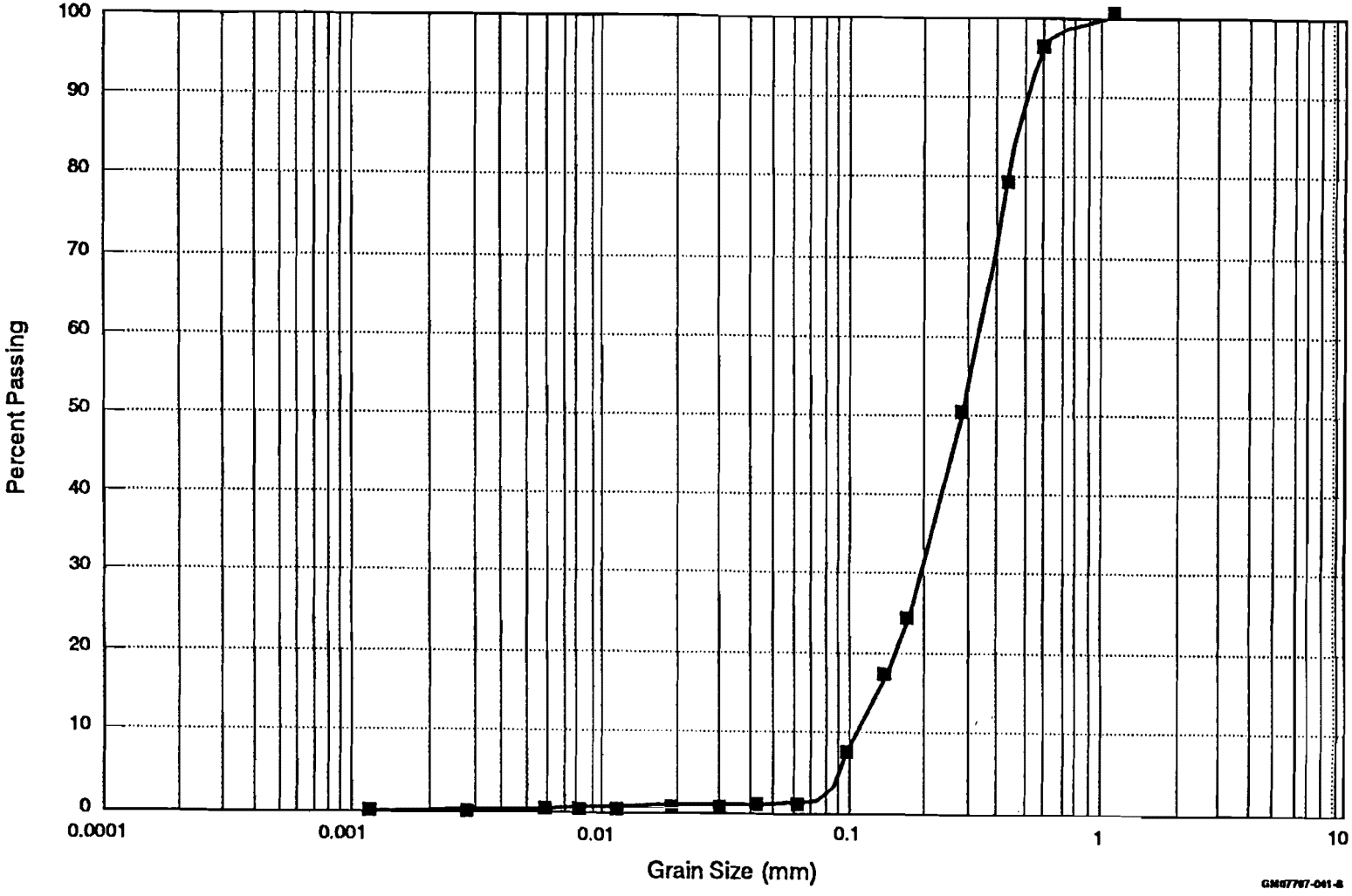


Figure 54. Grain size distribution curve (16.5 to 17.1 metres).

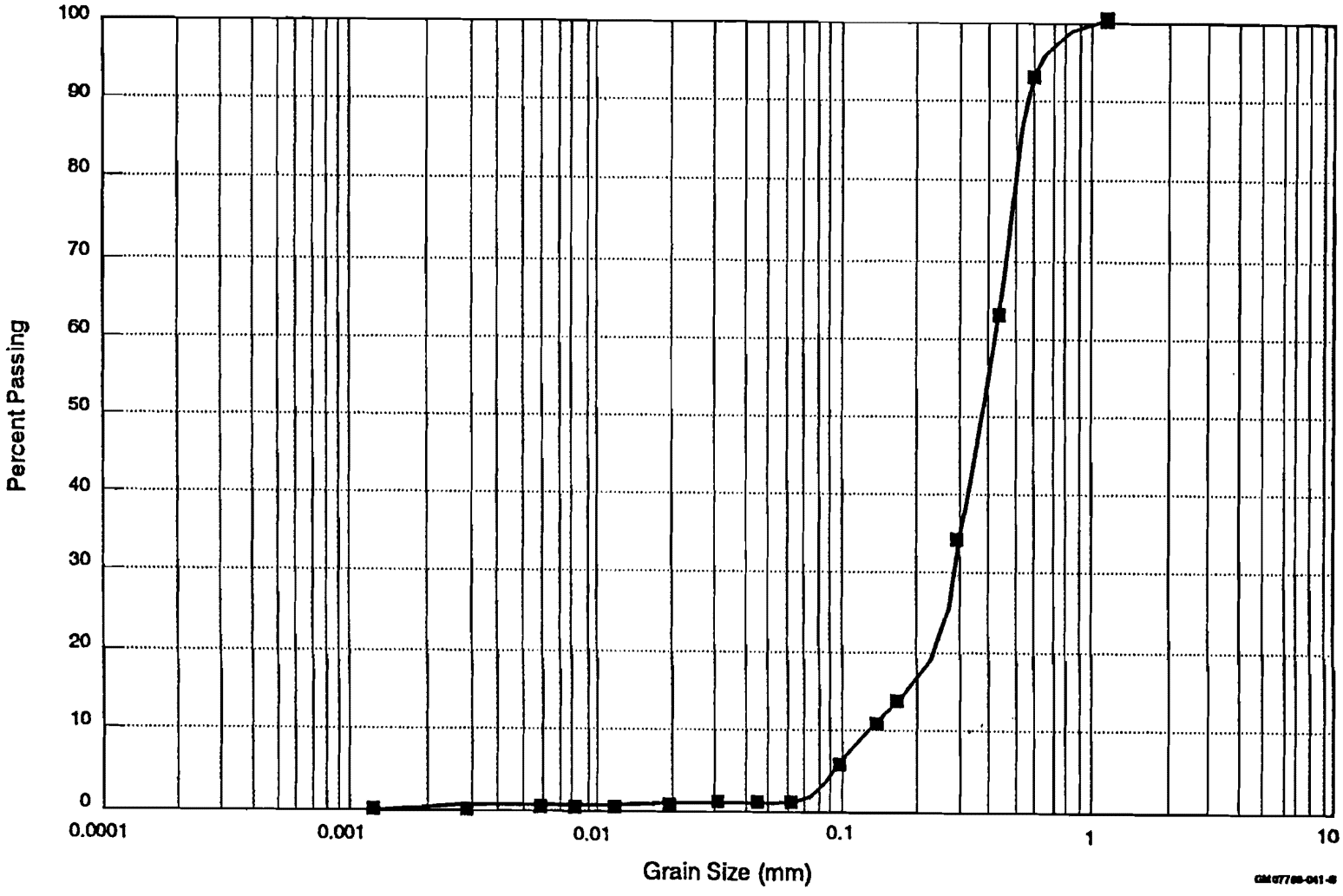


Figure 55. Grain size distribution curve (17.1 to 17.7 metres).

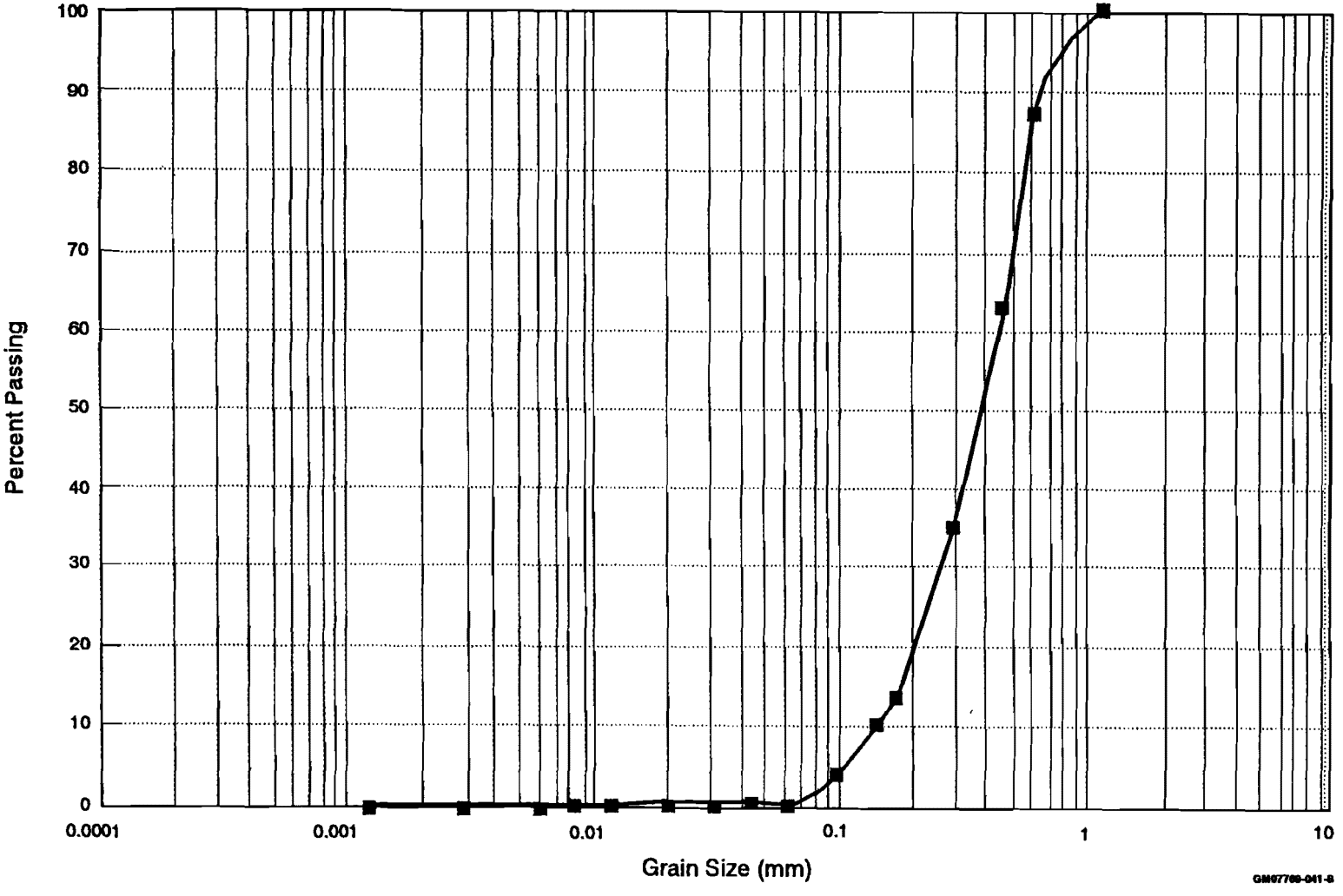


Figure 56. Grain size distribution curve (17.7 to 18.3 metres).

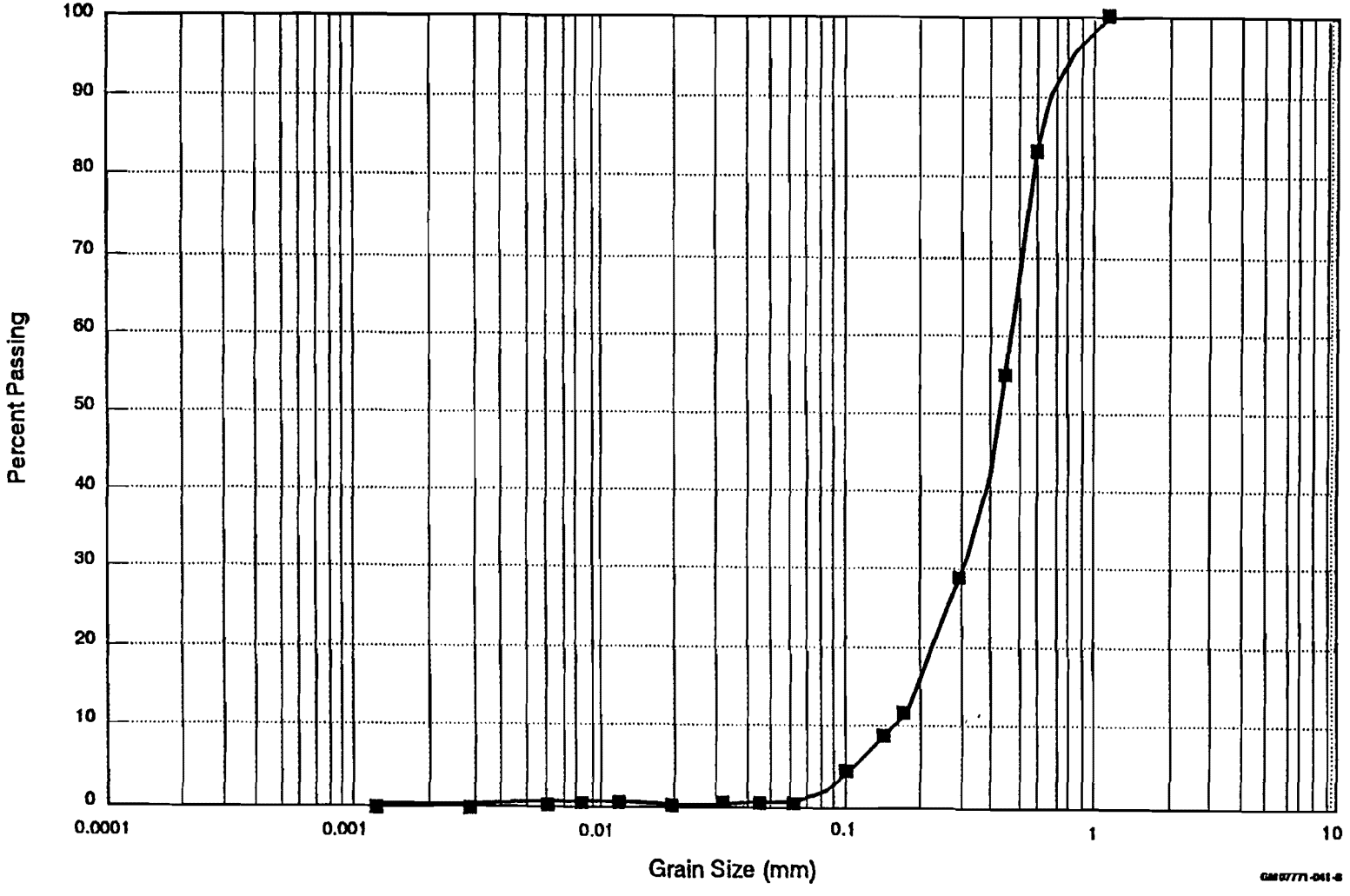


Figure 57. Grain size distribution curve (18.3 to 18.9 metres).

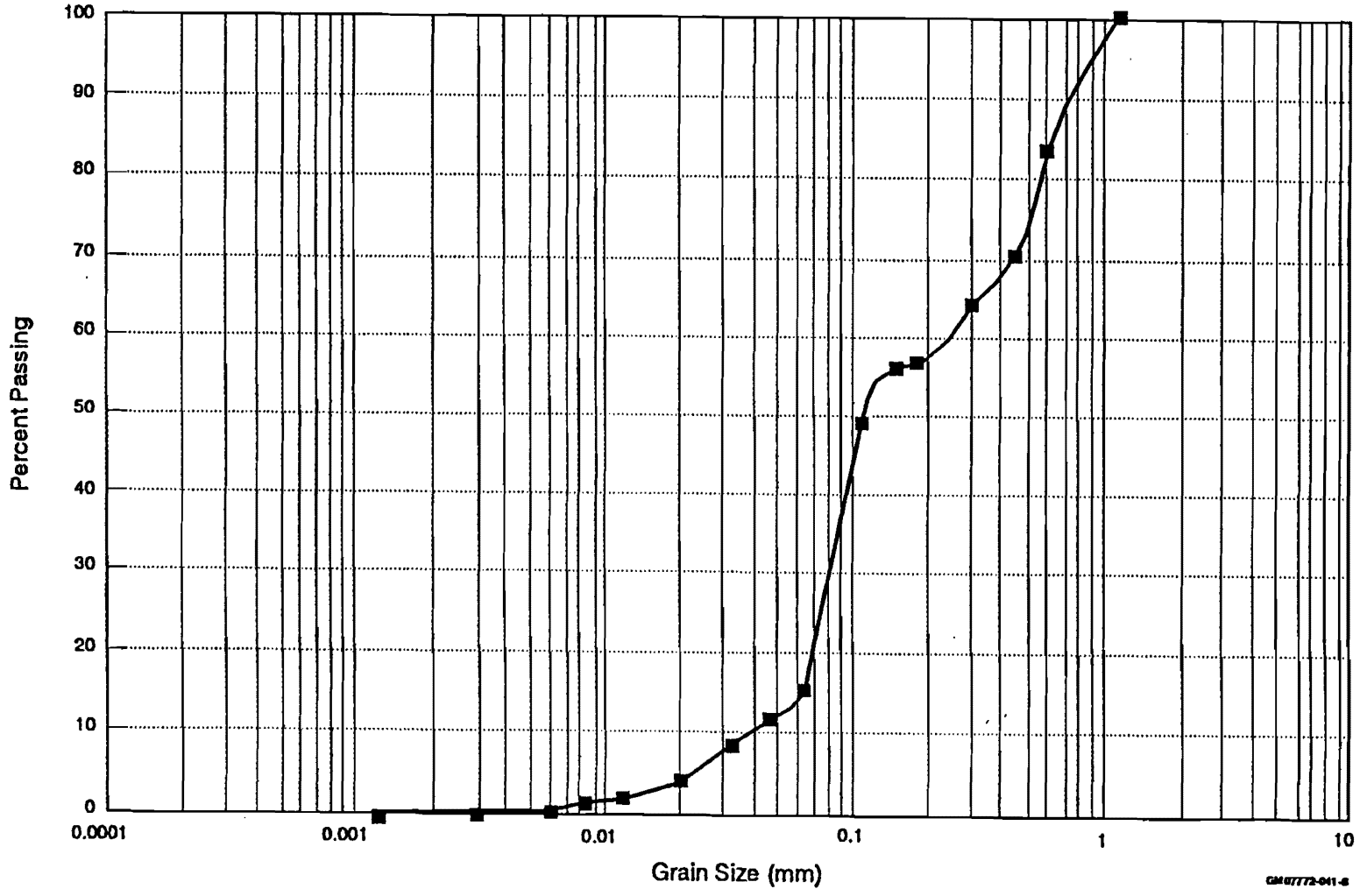


Figure 58. Grain size distribution curve (18.9 to 19.5 metres).

APPENDIX XIII

MODELING RESULTS

Appendix XIII

MODFLOW was used to simulate intermittent pumping of an irrigation well at the Elk Valley site. A grid size of 627,581 square metres (792.2 metres by 792.2 metres) by 12.2 metres thick was used and consisted of 25 rows, 25 columns, and 10 layers. Grid spacing was variable with row and column widths decreasing towards the irrigation well which was located in the center of the grid (Cell; 13,13). Column and row spacing was as follows:

Column or row number	Column or row width (metres)
1, 25	6.1
2, 24	39.0
3, 23	39.0
4, 22	39.0
5, 21	39.0
6, 20	39.0
7, 19	39.0
8, 18	39.0
9, 17	39.0
10, 16	39.0
11, 15	19.5
12, 14	14.6
13	9.8

Each of the ten layers was 1.22 metres thick with the irrigation well being screened in the lower five layers only. The well discharge rate was 3270.6 m^3/day (654.1 m^3/day per layer). A constant head boundary of 12.2 metres surrounded the grid (rows and columns - 1 and 25). Initial heads in all ten layer were set at 12.2 metres.

Sixteen stress periods consisting of eight pumping and eight recovery periods were used. The length of each of the well-pumping stress periods was two days and the length of each of the recovery periods was five days with the exception of the final recovery period which was 300 days. Each of the well-pumping stress periods had four time steps and the recovery periods ten time steps.

For this model, the aquifer was considered to be homogeneous and isotropic. Aquifer parameters included a horizontal hydraulic conductivity of 32 metres/day, a vertical hydraulic conductivity of 7.9 metres/day, and primary and secondary specific yields of 0.15.

Output from MODFLOW follows and includes hydraulic head data for row 13, layers 1 to 10, columns 1 to 13. This format allows the reader to view the table as a "slice" through the aquifer from the well to the outer boundary of the problem setup and observe hydraulic head changes that

occur with depth and distance from the well. Output is provided for the final time step of each stress period and also for all time steps in the final 300-day recovery period.

MODFLOW MODEL OF IRRIGATION PUMPING
END OF STRESS PERIOD # 1
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.94	10.76	11.86
2	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.29	10.47	11.58
3	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.25	10.14	11.18
4	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.21	9.75	10.54
5	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.17	9.28	9.45
6	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.13	8.72	7.47
7	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.09	8.29	6.40
8	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.06	7.99	5.81
9	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.04	7.80	5.50
10	12.20	12.20	12.20	12.20	12.20	12.20	12.20	12.19	12.18	12.10	11.03	7.70	5.37

END OF STRESS PERIOD # 2
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
2	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
3	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
4	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
5	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
6	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
7	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
8	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
9	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07
10	12.20	12.20	12.20	12.20	12.20	12.19	12.19	12.17	12.15	12.11	12.08	12.07	12.07

END OF STRESS PERIOD # 3
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.16	12.13	12.03	11.72	11.24	10.67
2	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	11.20	10.38
3	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	11.16	10.05
4	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	11.12	9.65
5	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	11.08	9.19
6	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	11.03	8.62
7	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	11.00	8.20
8	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	10.97	7.90
9	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	10.95	7.70
10	12.20	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.13	12.03	11.72	10.94	7.61

END OF STRESS PERIOD # 4
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.02
2	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.02
3	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.02
4	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.02
5	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.01
6	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.01
7	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.03	12.02	12.01
8	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.02	12.02	12.01
9	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.02	12.02	12.01
10	12.20	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.11	12.06	12.02	12.02	12.01

END OF STRESS PERIOD # 5
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.98	11.67	11.19	10.62
2	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.68	11.16	10.33
3	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.68	11.12	10.00
4	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.68	11.07	9.61
5	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.67	11.03	9.14
6	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.67	10.99	8.57
7	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.67	10.95	8.15
8	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.67	10.92	7.85
9	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.67	10.90	7.66
10	12.20	12.20	12.19	12.19	12.19	12.18	12.17	12.14	12.10	11.99	11.67	10.89	7.56

END OF STRESS PERIOD # 6
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.09	12.03	12.00	11.98	11.98
2	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
3	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
4	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
5	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
6	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
7	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
8	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
9	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98
10	12.20	12.20	12.19	12.19	12.18	12.17	12.16	12.13	12.08	12.03	11.99	11.98	11.98

END OF STRESS PERIOD # 7
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	11.16	10.59
2	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.65	11.13	10.30
3	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.65	11.08	9.96
4	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.65	11.04	9.57
5	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	11.00	9.11
6	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	10.95	8.54
7	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	10.92	8.12
8	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	10.89	7.82
9	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	10.87	7.63
10	12.20	12.20	12.19	12.19	12.18	12.17	12.15	12.12	12.07	11.96	11.64	10.86	7.53

END OF STRESS PERIOD # 8
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.01	11.97	11.96	11.96
2	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.01	11.97	11.96	11.96
3	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.01	11.97	11.96	11.95
4	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.01	11.97	11.96	11.95
5	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.00	11.97	11.95	11.95
6	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.00	11.97	11.95	11.95
7	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.00	11.97	11.95	11.95
8	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.00	11.97	11.95	11.95
9	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.00	11.97	11.95	11.95
10	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.06	12.00	11.97	11.95	11.95

END OF STRESS PERIOD # 9
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	11.14	10.56
2	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	11.10	10.27
3	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	11.06	9.94
4	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	11.02	9.55
5	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	10.97	9.08
6	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	10.93	8.52
7	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	10.89	8.09
8	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	10.87	7.79
9	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	10.84	7.60
10	12.20	12.19	12.19	12.18	12.17	12.16	12.14	12.11	12.05	11.94	11.62	10.84	7.51

END OF STRESS PERIOD # 10
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.99	11.95	11.94	11.94
2	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.94
3	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.94
4	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.93
5	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.93
6	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.93
7	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.93
8	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.94	11.93
9	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.93	11.93
10	12.20	12.19	12.19	12.18	12.17	12.15	12.13	12.09	12.05	11.98	11.95	11.93	11.93

END OF STRESS PERIOD # 11
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	11.12	10.54
2	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	11.08	10.25
3	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	11.04	9.92
4	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	11.00	9.53
5	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	10.95	9.06
6	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	10.91	8.50
7	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	10.88	8.08
8	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	10.84	7.77
9	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	10.83	7.58
10	12.20	12.19	12.19	12.18	12.16	12.15	12.13	12.09	12.04	11.92	11.60	10.81	7.49

END OF STRESS PERIOD # 12
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.92
2	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.92
3	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.92
4	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.92
5	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.92
6	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.92
7	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.91
8	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.91
9	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.91
10	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.03	11.97	11.93	11.92	11.91

END OF STRESS PERIOD # 13
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.90	11.59	11.10	10.52
2	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.90	11.59	11.06	10.23
3	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.59	11.02	9.90
4	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.59	10.98	9.51
5	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.59	10.94	9.05
6	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.59	10.90	8.48
7	12.20	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.59	10.86	8.06
8	12.19	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.59	10.83	7.76
9	12.19	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.58	10.81	7.56
10	12.19	12.19	12.18	12.17	12.16	12.14	12.12	12.08	12.02	11.91	11.58	10.80	7.47

END OF STRESS PERIOD # 14
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.96	11.92	11.91	11.91
2	12.20	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.96	11.92	11.91	11.91
3	12.20	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.96	11.92	11.91	11.91
4	12.20	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.96	11.92	11.91	11.90
5	12.20	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.95	11.92	11.91	11.90
6	12.19	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.95	11.92	11.91	11.90
7	12.19	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.95	11.92	11.91	11.90
8	12.19	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.95	11.92	11.90	11.90
9	12.19	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.95	11.92	11.90	11.90
10	12.19	12.16	12.18	12.17	12.16	12.13	12.11	12.07	12.02	11.95	11.92	11.90	11.90

END OF STRESS PERIOD # 15
(Hydraulic heads in metres)

CELL #	1	2	3	4	5	6	7	8	9	10	11	12	13
LAYER													
1	12.20	12.19	12.18	12.17	12.15	12.13	12.10	12.07	12.01	11.89	11.57	11.09	10.51
2	12.20	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	11.05	10.22
3	12.20	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	11.01	9.89
4	12.20	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	10.97	9.50
5	12.20	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	10.92	9.00
6	12.19	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	10.88	8.47
7	12.19	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	10.84	8.05
8	12.19	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	10.82	7.74
9	12.19	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.89	11.57	10.80	7.55
10	12.19	12.19	12.18	12.17	12.15	12.13	12.11	12.07	12.01	11.90	11.57	10.79	7.46

STRESS PERIOD # 16; END OF TIME STEP # 1
(Hydraulic heads in metres)

CELL #	1	2	3	4	5	6	7	8	9	10	11	12	13
LAYER													
1	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.83	11.77	11.74
2	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.83	11.76	11.73
3	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.83	11.76	11.72
4	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.82	11.75	11.71
5	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.82	11.75	11.70
6	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.82	11.75	11.69
7	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.82	11.74	11.68
8	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.93	11.82	11.74	11.68
9	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.92	11.82	11.74	11.67
10	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.06	12.01	11.92	11.82	11.74	11.67

STRESS PERIOD # 16; END OF TIME STEP # 2
(Hydraulic heads in metres)

CELL #	1	2	3	4	5	6	7	8	9	10	11	12	13
LAYER													
1	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.97	11.95	11.95
2	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
3	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
4	12.20	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
5	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
6	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
7	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
8	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
9	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95
10	12.19	12.19	12.18	12.16	12.15	12.13	12.10	12.07	12.03	11.99	11.96	11.95	11.95

STRESS PERIOD # 16; END OF TIME STEP # 3
(Hydraulic heads in metres)

CELL #	1	2	3	4	5	6	7	8	9	10	11	12	13
LAYER													
1	12.20	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.04	12.03	12.03
2	12.20	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.04	12.03	12.03
3	12.20	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.04	12.03	12.03
4	12.20	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.04	12.03	12.03
5	12.19	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.04	12.03	12.03
6	12.19	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.03	12.03	12.03
7	12.19	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.03	12.03	12.03
8	12.19	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.03	12.03	12.03
9	12.19	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.03	12.03	12.03
10	12.19	12.19	12.17	12.16	12.15	12.13	12.11	12.09	12.06	12.05	12.03	12.03	12.03

STRESS PERIOD # 16; END OF TIME STEP # 4
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
2	12.20	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
3	12.20	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
4	12.20	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
5	12.19	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
6	12.19	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
7	12.19	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
8	12.19	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
9	12.19	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08
10	12.19	12.19	12.18	12.16	12.15	12.14	12.12	12.11	12.09	12.09	12.08	12.08	12.08

STRESS PERIOD # 16; END OF TIME STEP # 5
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
2	12.20	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
3	12.20	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
4	12.20	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
5	12.19	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
6	12.19	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
7	12.19	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
8	12.19	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
9	12.19	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11
10	12.19	12.16	12.18	12.17	12.16	12.15	12.14	12.13	12.12	12.12	12.11	12.11	12.11

STRESS PERIOD # 16; END OF TIME STEP # 6
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
2	12.20	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
3	12.20	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
4	12.20	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
5	12.20	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
6	12.20	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
7	12.19	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
8	12.19	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
9	12.19	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14
10	12.19	12.19	12.18	12.17	12.17	12.16	12.15	12.15	12.14	12.14	12.14	12.14	12.14

STRESS PERIOD # 16; END OF TIME STEP # 7
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
2	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
3	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
4	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
5	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
6	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
7	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
8	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
9	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16
10	12.20	12.19	12.19	12.18	12.18	12.17	12.17	12.16	12.16	12.16	12.16	12.16	12.16

STRESS PERIOD # 16; END OF TIME STEP # 8
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
2	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
3	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
4	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
5	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
6	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
7	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
8	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
9	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
10	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17

STRESS PERIOD # 16; END OF TIME STEP # 9
(Hydraulic heads in metres)

CELL # LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
2	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
3	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
4	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
5	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
6	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
7	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
8	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
9	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
10	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17

STRESS PERIOD # 16; END OF TIME STEP # 10
(Hydraulic heads in metres)

CELL # / LAYER	1	2	3	4	5	6	7	8	9	10	11	12	13
1	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
2	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
3	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
4	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
5	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
6	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
7	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
8	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
9	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17
10	12.20	12.19	12.19	12.19	12.18	12.18	12.18	12.18	12.18	12.17	12.17	12.17	12.17

REFERENCES

Alexander, M., 1977, Introduction to Soil Microbiology: John Wiley and Sons, Inc., New York, 467 p.

American Public Health Association (APHA), 1980, Standard methods for the examination of water and wastewater: 15th Edition, APHA-AWWA-WPCF, American Public Health Association, Washington, DC, 1134 p.

ASTM, 1988, ASTM D422 Standard method for particle-size analysis of soils: Annual Book of ASTM Standards, sec. 4, v. 04.08, Soil and Rock; Building Stones, American Society for Testing and Materials, Philadelphia, Pennsylvania, p. 87-93.

Bartlett, M.S., Brown, L.C., Hanes, N.B., and Nickerson, N.H., 1979, Denitrification in freshwater wetland soil: Journal of Environmental Quality, v. 8, no. 4, p. 460-464.

Burford, J.R. and Bremner, J.M., 1975, Relationships between the denitrification capacities of soils and total, water-soluble and readily decomposable soil organic matter: Soil Biology and Biochemistry, v. 7, p. 389-394.

Bouwer, H., 1989, The Bouwer and Rice slug test - an update: Ground Water, v. 27, no. 3, p. 15-20.

Broadbent, F.E. and Clark, F., 1965, Denitrification: In Soil Nitrogen, W.V. Bartholemew and F.E. Clark (ed.), American Society of Agronomy, Madison, Wisconsin, p. 344-359.

Champ, D.R., Gulens, J., and Jackson, R.E., 1979, Oxidation-reduction sequences in ground water flow systems: Canadian Journal of Earth Sciences, v. 16, p. 12-23.

Code of Federal Regulations, 1990, Protection of the Environment: Maximum contaminant levels for inorganic chemicals: 40 CFR Ch.1, Part 141, Subpart B - 141.11, United States Printing Office, Washington, DC, p. 559-560.

Comly, H.H., 1945, Cyanosis in infants caused by nitrate in well water: Journal of American Medical Association, v. 129, no. 2, p. 112-116.

Delwiche, C.C. and Bryan, B.A., 1976, Denitrification: Annual Review of Microbiology, v. 30, p. 241-262.

Doolittle, J.A., Heidt, C.J., Stuart, J.L., Ryterske, T.P., Ulmer, M.G., and Wellman, P.E., 1981, Soil survey of Grand Forks County, North Dakota: United States Department of Agriculture, Soil Conservation Service, 191 p.

Drimmie, R.J., Heemskerk, A.R., and Johnson, J.C., 1991, Tritium analysis: Technical Procedure 1.0, Revision 02, Environmental Isotope Laboratory: Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, 32 p.

Foster, S.S.D., Kelly, D.P., and James, R., 1985, The evidence for biodenitrification in British aquifers: In Planetary Ecology (D.E. Caldwell, J.A. Brierly, and C.L. Brierly - editors), Van Nostrand Reinhold, New York, p. 356-369.

Fraser, P. and Chilvers, D., 1980, Health aspects of nitrate in drinking water: The Science of the Environment, Water Supply and Health, Studies in Environmental Science, v. 12, p. 103-116.

Freeze, R.A. and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 p.

Gamble, T.N., Berlach, M.R., and Tiedje, J.M., 1977, Numerically dominant denitrifying bacteria from world soils: Applied Environmental Microbiology, v. 33, p. 926-939.

Gayon, U. and Dupetit, G., 1886, Recherches sur la reduction des nitrates par les infiniments petits: Society des Sciences Physiques et Naturelles de-Bordeaux, ser. 3, v. 2, p. 201-307.

Gerla, P.J., Sahl, B.L., and Mayer, G.G., 1992, Nitrate impact to a shallow aquifer in an area of dryland farming: Submitted for publication in Journal of Soil and Water Conservation.

Gillham, R.W. and Cherry, J.A., 1978, Field evidence of denitrification in shallow groundwater flow systems: Water Pollution Research in Canada, v. 13, p. 53-71.

Hammond, P.D. and Goodman J., 1992, Pesticides and nitrates in surficial aquifers in some agricultural areas in South Dakota: Presention at the 37th Annual Midwest Ground Water Conference, Sioux Falls, South Dakota.

Hansen, D.E. and Kume, J., 1970, Geology and ground water resources of Grand Forks County: Part I--Geology: North Dakota Geological Survey Bulletin 53, 76 p.

Hauck, R.D., 1986, Field measurement of denitrification--an overview: Soil Science Society of America Symposium Proceedings, Soil Science Society of America Special Publication no. 18, p. 59-72.

Hutchinson, M., Johnstone, K.I., and White, D., 1967, Taxonomy of anaerobic thiobacilli: Journal of General Microbiology, v. 47, p. 17-23.

Jaffe, E.R., 1981, Methemoglobinemia: Clinical Hematology, v. 10, p. 99-122.

Kelly, T.E., 1968, Geology and ground water resources of Grand Forks County: Part II--Ground water basic data: North Dakota Geological Survey Bulletin 53, 117 p.

Kelly, T.E. and Paulson, Q.R., 1970, Geology and ground water resources of Grand Forks County: Part III--Ground water resources: North Dakota Geological Survey Bulletin 53, 58 p.

Knowles, R., 1982, Denitrification: Microbiological Reviews, v. 46, no. 1, p. 43-70.

Korom, S.F., 1992, Natural denitrification in the saturated zone: a review: Water Resources Research, v. 26, no. 6, p. 1657-1668.

Lind A. and Pedersen, M.B., 1976, Nitrate reduction in the subsoil: Tidsskrift for Planteavl, v. 80, p. 73-118.

Lowrance, R.R. and Pionke, H.B., 1989, Transformations and movement of nitrate in aquifer systems: in Nitrate Management and Groundwater Protection - Developments in Agricultural and Managed-Forest Ecology 21 (R.F. Follett - editor), Elsevier Science Publishers B.V., Amsterdam, The Netherlands, p. 373-392.

Matthes, G., 1985, Geochemical conditions in the groundwater environment: in Planetary Ecology (D.E. Caldwell, J.A. Brierly, and C.L. Brierly - editors), Van Nostrand Reinhold, New York, p. 347-355.

McCarty, P.L., Rittman, B.E., and Bouwer, E.J., 1984, Microbial processes affecting chemical transformations in groundwater: in Groundwater Pollution Microbiology (G. Bitton and C.P. Gerba - editors), John Wiley and Sons, Inc., N.Y., p. 89-115.

McDonald, M.G. and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of water-resources investigations of the United States Geological Survey, Book 6, Chapter A1, United States Government Printing Office, Washington, DC, 589 p.

Nommik, H., 1956, Investigations on denitrification in soil: Acta Agriculturae Scandinavica, v. 6, p. 195-228.

Pontius, F.W., 1992, A current look at the federal drinking water regulations: American Water Works Association Journal, v. 84, p. 36-50.

Rolston, D.E., 1986, Limitations of the acetylene blockage technique for field measurement of denitrification: Soil Science Society of America Symposium Proceedings, Soil Science Society of America Special Publication no. 18, p. 93-101.

Shuval, H.I. and Gruner, N., 1972, Epidemiology and toxicological aspects of nitrates and nitrites in the environment: American Journal of Public Health, v. 210, p. 347-350.

Solomon, D.K., Poreda, R.J., Schiff, S.L., and Cherry, J.A., 1992, Tritium and helium 3 as groundwater age tracers in the Borden Aquifer: Water Resources Research, v. 28, no. 3, p. 741-755.

Starr, R.C. and Gillham, R.W., 1989, Controls on denitrification in shallow unconfined aquifers: in Contaminant Transport in Groundwater, edited by H.E. Kobus and W. Kinzelbach, A.A. Balkema, Rotterdam, p. 51-56.

Taylor, C.B., 1977, Tritium enrichment of environmental waters by electrolysis: Development of cathodes exhibiting high isotopic separation and precise measurement of tritium enrichment factors, Proceedings of the International Conference of Low-Radioactivity Measurements and Applications, Slovenski Pedagogicke Nakladatelstvo, Bratislava, p. 131-140.

Tiedje, J.M., 1982, Denitrification: in Methods of Soil Analysis - Part 2, American Society for Agronomy, Madison, Wisconsin, p. 1011-1026.

Tonneson, L., 1991, The Valley's new gold rush: The Dakota Farmer, v. 108, p. 28a-28d.

Trudell, M.R., Gillham, R.W., and Cherry, J.A., 1986, An in-situ study of the occurrence and rate of denitrification in a shallow unconfined sand aquifer: Journal of Hydrology, v. 83, p. 141-268.

Wijler, J. and Delwiche, C.C., 1954, Investigations on the denitrifying process in soil: Plant and Soil, v. 5, no. 2, p. 155-169.

Zheng, C., 1991, User's manual: PATH3D, a ground-water path and travel-time simulator, S.S. Papadopulos and Associates, Inc., Rockville, Maryland, 78 p.

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